(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
6 February 2003 (06.02.2003)

PCT

(10) International Publication Number
WO 03/010592 A2

(51) International Patent Classification[7]: G02F 1/01, 1/065

(21) International Application Number: PCT/US02/22139

(22) International Filing Date: 12 July 2002 (12.07.2002)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
09/916,238 26 July 2001 (26.07.2001) US
10/098,730 15 March 2002 (15.03.2002) US

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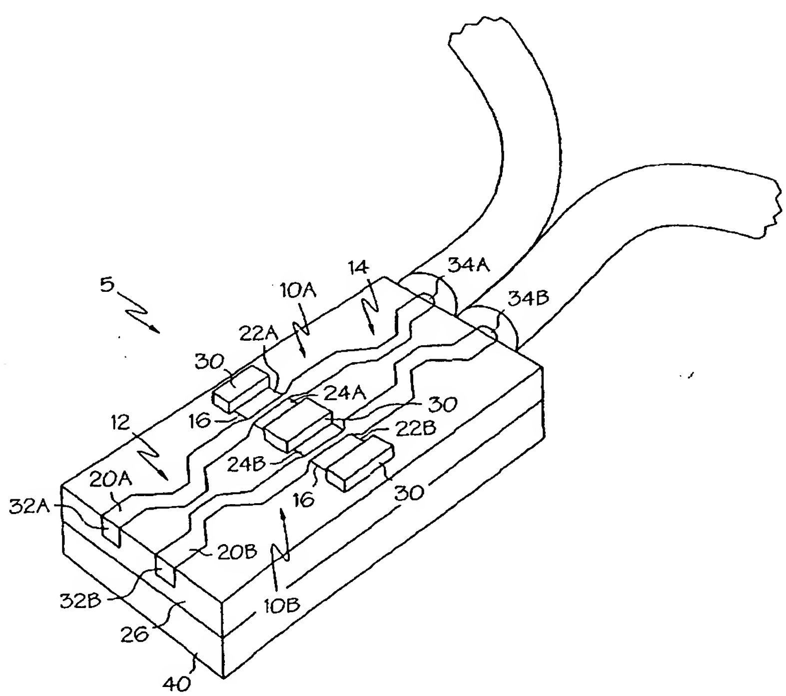
(81) Designated States (national): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, OM, PH, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, UZ, VN, YU, ZA, ZM, ZW.

(84) Designated States (regional): ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, SK,

*[Continued on next page]*

# (54) Title: WAVEGUIDES AND DEVICES INCORPORATING OPTICALLY FUNCTIONAL CLADDING REGIONS




**(57) Abstract:** Waveguides and integrated optical devices incorporating optically functional cladding regions are provided. In accordance with one embodiment of the present invention, an electrooptic clad waveguide is provided with an optical waveguide core and first and second electrooptic cladding regions. The optical waveguide core is a substantially non-electrooptic material. The cladding regions are electrooptic polymers defining a refractive index that is less than that of the core. The first and second cladding regions may be poled in opposite or perpendicular directions or along a contour of an electric field. Additional embodiments of the present invention utilize other types of optically functional materials in the cladding regions. Integrated optical devices according to the present invention comprise phase modulators, intensity modulators, 2x2 polarization independent optical switches, high-frequency modulators, wavelength-dependent optical switches, directional couplers employing electrooptic gaps and electrooptic cladding regions, and optical devices with thinned-down waveguide channels and phase compensating elements.

WO 03/010592 A2

TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

**Published:**

— *without international search report and to be republished upon receipt of that report*

*For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.*

# WAVEGUIDES AND DEVICES INCORPORATING OPTICALLY FUNCTIONAL CLADDING REGIONS

The present invention relates to optical signal transmission and, more specifically, an improved optical waveguide useful in applications requiring modulation and switching of optical signals.

It is becoming increasingly important to frequently upgrade telecommunication networks to increase their capacity due to the recent rapid increase in network traffic caused by multimedia communications. Although optical technologies are replacing most transmission lines, the nodes of optical networks, such as switching and cross-connect nodes, still depend on relatively slow electrical technologies. Specifically, time-division multiplexing (TDM) systems are widely used in existing optical communications systems and are inherently dependent on electrical circuits for multiplexing and demultiplexing. As a result, the electrical nodes in these types of optical networks limit throughput.

Accordingly, there is a need in the art for advances in telecommunication network design. More specifically, there is a need for innovation in the areas of switching, modulation, multiplexing and demultiplexing via optical technologies.

This need is met by the present invention wherein waveguides and integrated optical devices incorporating optically functional cladding regions are provided. A significant advantage of many embodiments of the present invention lies in the use of two or more electrooptic cladding regions that are, through appropriate poling and/or deposition procedures, oriented with their polar axes in different directions. This type of orientation and variations thereof, as described herein, allow for production of waveguides and integrated optical devices exhibiting unique functionality and allowing for optimum flexibility in device design. The waveguides and integrated optical devices described herein may be exploited in various ways, many of which are described herein.

In accordance with one embodiment of the present invention, an electrooptic clad waveguide is provided comprising an optical waveguide core and first and second cladding regions. The optical waveguide core defines a primary axis of propagation $z$. The first cladding region is offset from the $z$ axis in a first direction along an $x$ axis perpendicular to the $z$ axis. The second cladding region is offset from the $z$ axis in a

second direction along the $x$ axis. The optical waveguide core comprises a substantially non-electrooptic material defining a refractive index $n_1$ and the first and second cladding regions comprises an electrooptic polymer defining a refractive index that is less than $n_1$. The first and second cladding regions may be poled in opposite or perpendicular directions.

In accordance with another embodiment of the present invention, an electrooptic clad waveguide is provided where first and second control electrodes are arranged to enable electrooptic modification of the refractive indices of the first and second cladding regions by creating a contoured electric field in the first and second cladding regions. The contoured electric field and the respective directions of polarization in the first and second cladding regions define a polarization-independent waveguide structure along the primary axis of propagation of the electrooptic clad waveguide. Preferably, the first and second cladding regions are poled along substantially the same contour of the electric field.

In accordance with yet another embodiment of the present invention, an integrated optical device is provided comprising an optical input, an optical output, an electrooptic clad waveguide, and first and second control electrodes. The electrooptic clad waveguide is arranged along an optical path defined between the optical input and the optical output. The electrooptic clad waveguide is characterized by an optical phase delay $\Phi=2\pi L n_{eff}/\lambda$, where $n_{eff}$ is the effective index of refraction of the waveguide, L is the length over which the phase delay occurs, and $\lambda$ is the wavelength of light propagating along the optical path. The electrooptic clad waveguide comprises an optical waveguide core defining a primary axis of propagation $z$, a first cladding region offset from the $z$ axis in a first direction along an $x$ axis perpendicular to the $z$ axis, and a second cladding region offset from the $z$ axis in a second direction along the $x$ axis. The optical waveguide core comprises a substantially non-electrooptic material defining a refractive index $n_1$. The first and second cladding regions comprise an electrooptic polymer defining a refractive index that is less than $n_1$. The waveguide core defines a cross-sectional $x$ axis width that decreases from a region outside of the first and second cladding regions to a region bounded by the first and second cladding regions. The first and second control electrodes are arranged to create an electric field in the first and second cladding regions capable of changing the refractive indices of the first and second electrooptic cladding regions without a corresponding

change in the refractive index $n_1$ of the waveguide core so as to induce a core-independent change in $n_{eff}$ and a corresponding change in the optical phase delay $\Phi$ of the waveguide.

In accordance with yet another embodiment of the present invention, an electrooptic waveguide for an optical signal is provided. The waveguide comprises a plurality of control electrodes, an optical waveguide core, and electrooptic cladding regions optically coupled to the optical waveguide core. The control electrodes are positioned to generate a contoured electric field across the cladding. The cladding is poled along a poling contour. The cladding defines an array of local TM indices of refraction $n_{TM}$ corresponding to the indices of refraction for the vertically oriented component TM of the optical signal in the cladding. The cladding also defines an array of local TE indices of refraction $n_{TE}$ corresponding to the indices of refraction for the horizontally oriented component TE of the optical signal in the cladding. The local TM indices $n_{TM}$ and the local TE indices $n_{TE}$ are each a function of a first electrooptic coefficient $r_{PP}$ for light parallel to a local component of the contoured electric field and a second electrooptic coefficient $r_{IP}$ for light perpendicular to a local component of the contoured electric field. The difference between the first and second electrooptic coefficients $r_{PP}$ and $r_{IP}$ defines an optical birefringence of an electrooptic cladding material defining the cladding. The local TM indices $n_{TM}$ collectively define a TM mode index of the waveguide. The local TE indices $n_{TE}$ collectively define a TE mode index of the waveguide. The respective orientations of the contoured electric field and the poling contour are configured to compensate for the optical birefringence of the electrooptic cladding material such that the TM mode index of the waveguide is substantially equal to the TE mode index of the waveguide.

In accordance with yet another embodiment of the present invention, an electrooptic waveguide for an optical signal is provided. The waveguide comprises a plurality of control electrodes, an optical waveguide core defining a primary axis of propagation, and an electrooptic cladding at least partially surrounding the core. The control electrodes are positioned to generate a contoured electric field across the cladding. The cladding is poled along a poling contour. Either the contoured electric field, the poling contour, or both are asymmetric.

In accordance with yet another embodiment of the present invention, an

electrooptic waveguide for an optical signal is provided. The waveguide comprises a plurality of control electrodes, an electrooptic optical waveguide core defining a primary axis of propagation, and a cladding at least partially surrounding the core. The control electrodes are positioned to generate a contoured electric field across the core. The core is poled along a poling contour. Either the contoured electric field, the poling contour, or both are asymmetric.

In accordance with yet another embodiment of the present invention, a process is provided wherein an electrooptic waveguide is formed by: providing a waveguide substrate; positioning an optical waveguide core over a first surface of the substrate; providing a waveguide superstrate; forming at least two control electrodes on a first surface of the superstrate, wherein the control electrodes define selected electrode thicknesses; positioning a viscous electrooptic cladding material over one or both of the first surface of the substrate and the first surface of the superstrate; and urging the first surface of the waveguide substrate and the first surface of the waveguide superstrate toward each other to create a layer of cladding material between the surfaces. The cladding material, which is subsequently cured, defines a cladding material viscosity selected to permit dispersion of the cladding material about the control electrodes and the core as the first surface of the waveguide substrate and the first surface of the waveguide superstrate are urged toward each other. The cladding material is provided in a quantity sufficient to ensure that the layer of cladding material defines a cladding layer thickness at least as large as the selected electrode thicknesses.

In accordance with yet another embodiment of the present invention, an integrated optical device is provided where first and second waveguides are arranged to define a Mach-Zehnder interferometer. The interferometer includes first and second directional coupling regions, an intermediate coupling region disposed between the first and second directional coupling regions, a set of control electrodes, an optical input, and at least one optical output. One or both of the first and second waveguides comprise an electrooptic clad waveguide comprising a substantially non-electrooptic optical waveguide core defining a refractive index $n_1$. The waveguide core of the electrooptic clad waveguide is disposed between first and second cladding regions in the intermediate coupling region. The first and second cladding regions comprise a poled electrooptic polymer defining a refractive index that is less than $n_1$. The control electrodes are arranged to create an

electric field in the first and second cladding regions capable of changing the refractive indices of the first and second electrooptic cladding regions so as to induce a change in an effective index of refraction $n_{eff}$ of the electrooptic clad waveguide. The control electrodes are further arranged so that a quantitative combination of the electric field and the poling in the first cladding region is substantially equivalent to a quantitative combination of the electric field and the poling in the second cladding region. In this manner an output intensity $I_{out}$ at one of the optical outputs is related to an input intensity $I_{in}$ according to one of the following equations

$$|I_{out}|^2 = |I_{in}|^2 \sin^2\left(\frac{\phi}{2}\right)$$

$$|I_{out}|^2 = |I_{in}|^2 \cos^2\left(\frac{\phi}{2}\right)$$

where $\Phi$ represents optical phase delay resulting from the change in the effective index of refraction $n_{eff}$ of the electrooptic clad waveguide.

In accordance with yet another embodiment of the present invention, an integrated optical device is provided comprising first and second electrooptic clad waveguides arranged to define a Mach-Zehnder interferometer. The interferometer includes first and second directional coupling regions, an intermediate coupling region disposed between the first and second directional coupling regions, a set of control electrodes, first and second optical inputs, and first and second optical outputs. The waveguide core of the first waveguide is disposed between first and second cladding regions of the first waveguide in the intermediate coupling region. The waveguide core of the second waveguide is disposed between first and second cladding regions of the second waveguide in the intermediate coupling region. The poling of the first and second cladding regions of the first waveguide is substantially perpendicular to the poling of the first and second cladding regions of the second waveguide. The control electrodes are arranged to create an electric field in the first and second cladding regions of the first and second waveguides to induce a change in an effective index of refraction $n_{eff}$ of the first and second waveguides, whereby input optical signals may be directed selectively to separate ones of the optical outputs by controlling the electric field.

In accordance with yet another embodiment of the present invention, an integrated

optical device is provided comprising first and second waveguides arranged to define a Mach-Zehnder interferometer. The control electrodes of the device form a traveling wave stripline and are arranged to create an electric field in the first and second cladding regions capable of changing the refractive indices of the first and second electrooptic cladding regions so as to induce a change in an effective index of refraction $n_{eff}$ of the electrooptic clad waveguide. The traveling wave stripline is characterized by a dielectric constant $\varepsilon$ selected such that an optical signal propagating in the electrooptic clad waveguide propagates at the same velocity as an electrical signal propagating in the traveling wave stripline. The control electrodes are arranged such that a quantitative combination of the electric field and the poling in the first cladding region is substantially equivalent to a quantitative combination of the electric field and the poling in the second cladding region, whereby an output intensity $I_{out}$ at one of the optical outputs is related to an input intensity $I_{in}$ according to one of the following equations

$$|I_{out}|^2 = |I_{in}|^2 \sin^2\left(\frac{\phi}{2}\right)$$

$$|I_{out}|^2 = |I_{in}|^2 \cos^2\left(\frac{\phi}{2}\right)$$

where $\Phi$ represents optical phase delay resulting from the change in the effective index of refraction $n_{eff}$ of the electrooptic clad waveguide.

In accordance with yet another embodiment of the present invention, an integrated optical device is provided comprising first and second electrooptic clad waveguides of unequal length arranged to define an asymmetric Mach-Zehnder interferometer. The control electrodes are arranged to create an electric field in the first and second cladding regions of the first and second waveguides to induce a change in the effective index of refraction $n_{eff}$ of the first and second waveguides. In this manner, first and second wavelength components of an input optical signal may be directed selectively to separate ones of the optical outputs by controlling the electric field.

In accordance with yet another embodiment of the present invention, an integrated optical device is provided comprising first and second electrooptic clad waveguides arranged to define a directional coupling region. The waveguide core of the first waveguide is disposed between a first outer electrooptic cladding region and an

electrooptic gap region in the directional coupling region. The waveguide core of the second waveguide is disposed between a second outer electrooptic cladding region and the electrooptic gap region in the directional coupling region. The control electrodes are arranged to create an electric field across the outer cladding regions and the electrooptic gap region, whereby an optical signal incident in one of the waveguides may be switched to the other of the waveguides.

In accordance with yet another embodiment of the present invention, an optical waveguide is provided comprising a waveguide core defining a core height dimension $h$ that remains substantially constant between the optical input and the optical output. The core width dimension defines an input width $w_1$ at the optical input, an output width $w_2$ at the optical output, an increased-width $w_0$ along a phase compensating element of the waveguide core, and a decreased-width $w_3$ along a thinned-down portion of the waveguide core. The increased-width $w_0$ is greater than the input width and the decreased-width $w_3$ is less than the input width.

In accordance with yet another embodiment of the present invention, an optical waveguide is provided where the core width dimension defines an increased-width $w_0$ along a phase compensating element of the waveguide core and a decreased-width $w_3$ along a thinned-down portion of the waveguide core. The decreased-width $w_3$ is less than the core height dimension $h$ and the increased-width $w_0$ is greater than the core height dimension $h$.

In accordance with yet another embodiment of the present invention an integrated optical device is provided comprising a plurality of channel waveguides and a thermo/electric poling arrangement. At least a pair of the waveguides are at least partially bounded along a portion of their length by respective electrooptic cladding regions defining respective polar axes. The thermo/electric poling arrangement is provided proximate the respective electrooptic cladding regions and is arranged to orient independently the respective polar axes of the cladding regions.

Accordingly, it is an object of the present invention to provide improved optical waveguides and integrated optical devices useful in applications requiring modulation and switching of optical signals. Other objects of the present invention will be apparent in light of the description of the invention embodied herein.

The following detailed description of the preferred embodiments of the present invention can be best understood when read in conjunction with the following drawings, where like structure is indicated with like reference numerals and in which:

Figures 1-4 illustrate optical waveguides according to the present invention including electrooptic cladding regions poled in opposite directions;

Figure 5 illustrates an optical waveguide according to the present invention including electrooptic cladding regions poled in perpendicular directions;

Figure 6 illustrates an optical waveguide according to the present invention including electrooptic cladding regions poled along a contoured electric field;

Figs. 7 and 8 illustrate optical waveguides according to two different embodiments of the present invention;

Figs. 9 through 16 illustrate alternative electrode and waveguide core configurations according to the present invention;

Figs. 17-19 illustrate electrode and waveguide core configurations along a length dimension of an optical waveguide according to the present invention;

Figs. 20A through 20D illustrate a process for forming a waveguide according to the present invention;

Figs. 21 and 22 illustrate variations to the process of Figs. 14A-14D;

Figures 23-25 illustrate an integrated optical device according to the present invention including a thinned-down waveguide channel;

Figure 26 illustrates a polarization-independent optical intensity modulator or 2x2 optical switch according to the present invention;

Figure 27 illustrates a high-frequency electrooptic modulator according to the present invention;

Figure 28 illustrates a wavelength-dependent optical switch according to the present invention;

Figure 29 illustrates an integrated optical device according to the present invention including a specialized electrooptic directional coupler;

Figures 30A and 30B illustrate electrode and poling arrangements suitable for use in the integrated optical device of Figure 13;

Figure 31 illustrates schematically the relationship of TE and TM modes as an optical signal propagates through a reduced-width waveguide segment;

Figure 32 is a graphical representation of data that may be used to design an appropriate compensating waveguide segment; and

Figure 33 illustrates an increased-width phase compensating element according to the present invention.

The present invention is generally related to the use of poled polymeric electrooptic materials as cladding regions or layers around low loss non-electrooptic waveguide cores like silica waveguide cores. Electrooptic materials suitable for use in the present invention should have an index of refraction that is lower than the index of the waveguide core bounded by the cladding layers. Typically, the waveguide core is fabricated from doped silica and exhibits a refractive index $n_1$ of about 1.45 at 1550 nm. Conventional electrooptic materials exhibit a higher refractive index of about 1.6 at similar wavelengths.

Generally, the polymeric electrooptic materials include thermoplastic or thermosetting polymers that are blended or co-polymerized with an electrooptic chromophore. The thermoplastic or thermosetting polymer is typically selected from the group consisting of acrylics / methacrylics, polyesters, polyurethanes, polyimides, polyamides, polyphosphazenes, epoxy resins, and hybrid (organic-inorganic) or nanocomposite polyester polymers. Combinations of thermoplastic and thermosetting polymers (interpenetrating polymer networks) are also contemplated. The thermoplastic and/or thermosetting polymers typically have glass transition temperatures above 100°C. One embodiment for low-index materials has a refractive index value less than 1.5 while another embodiment for high-index materials has a refractive index value greater than 1.5. The polymers are combined with chromophores, either as part of the backbone chain or blended and typically contain compatibilization additives or groups and/or adhesion-promotion additives or groups. The electrooptic chromophore according to the invention is typically a substituted aniline, substituted azobenzene, substituted stilbene, or substituted imine.

Optical Channel Waveguides.

Figs. 1-4 illustrate schematically two types of optical channel waveguides 10 according to the present invention. Each of the optical waveguides illustrated in Figs. 1-4 employs oppositely poled cladding regions and a substantially non-electrooptic core. For

the purposes of defining and describing the present invention, it is noted that a substantially non-electrooptic material, silica for example, is a material that is not inherently electrooptic. Of course, substantially non-electrooptic materials may exhibit a small electrooptic effect under relatively high electric fields.

Referring further to Figs. 1-4, each electrooptic clad waveguide 10 comprises an optical waveguide core 20 and first and second cladding regions 22, 24. The optical waveguide core 20 defines a primary axis of propagation $z$ that lies substantially along the center of the waveguide core, running the length of the core 20. To preserve clarity, the $z$ axis is labeled in Figs. 1, 5, and 6 offset from the center of the waveguide core 20.

The first cladding region 22 is offset from the $z$ axis in a first direction along an $x$ axis perpendicular to the $z$ axis. The second cladding region 24 is offset from the $z$ axis in a second opposite direction along the $x$ axis. A set of control electrodes 30 are arranged to create an electric field E in the first and second cladding regions 22, 24 that alters the refractive index of the cladding regions. The waveguide 10 is supported by a substrate 40.

Those practicing the present invention familiar with optical waveguide technology will appreciate that a variety of materials are acceptable for use as the control electrodes 30, the under-cladding layer 26, and the substrate 40. For example, the control electrodes may be formed from gold. The core 20 may be formed from Ge-doped fused silica and is typically 8μm square in cross section. The substrate 40 is most commonly formed of silicon and may be about 0.5 mm thick. An under-cladding layer 26 (shown in Fig. 10) is also typically provided between the substrate 40 and the core 20 and may formed from at least 15 micron thick fused silica.

In the embodiments of Figs. 1 and 2, the first and second cladding regions 22, 24 are both vertically poled but each is poled in a different direction, as indicated by the directional arrows P. Similarly, in Figs. 3 and 4, the first and second cladding regions 22, 24 are both horizontally poled but each is poled in a different direction, as indicated by the directional arrows P. The first and second cladding regions 22, 24 of each embodiment are poled in opposite directions to ensure that the refractive indices of the cladding regions change in the same relative direction upon creation of the electric field E. More specifically, the refractive indices of the cladding regions 22, 24 on both sides of the core 20 either increase under the electric field E or decrease under the electric field E.

The above-described change in refractive index may be represented by the

following equation

$$\Delta n = -\frac{1}{2} n^3 r_{ij} E_j$$

where $r_{ij}$ is the Pockels electrooptic coefficient of the cladding region at issue and $E_j$ represents the strength and orientation of the applied electric field. The control electrodes 30 are preferably arranged such that the above-noted quantitative combination of the electric field and the poling in the first cladding region is substantially equivalent to a quantitative combination of the electric field and the poling in the second cladding region. It is contemplated by the present invention that other equations, formulas, or relations may be used to quantify the combination of the electric field and the poling in the cladding regions according to the present invention.

For the purposes of describing and defining the present invention, it is noted that TE and TM polarized light represent two independent electromagnetic modes of an optical signal. The electromagnetic field distribution is referred to as the transverse electric (TE) mode where the electric field of the optical signal lies in the plane that is perpendicular to the $z$-axis. The electromagnetic field distribution is referred to as the transverse magnetic (TM) mode where the magnetic field of the optical signal lies in the plane that is perpendicular to the $z$-axis. It is also noted that in a channel waveguide of the illustrated type, the propagating modes are not purely TE or TM polarized. Rather, the modes are typically more predominantly one or the other and are commonly so designated.

The present invention is particularly advantageous in the context of guiding non-polarized light, i.e., optical signals including both a horizontally oriented component TE and a vertically oriented component TM. Specifically, the optical waveguides described include electrode arrangements and poling configurations that provide for electrooptic responses that are insensitive to the polarization of the optical signal with or without a driving voltage applied to the electrodes.

In the waveguide arrangement of Figs. 1 and 2, TM polarized light propagating along the primary axis of propagation $z$ of the waveguide 10 encounters an ordinary change in refractive index $n_o$, upon creation of the electric field E, while TE polarized light propagating along the same path encounters an extraordinary change in refractive index $n_e$. In contrast, in the waveguide arrangement of Figs. 3 and 4, TM polarized light propagating along the primary axis of propagation $z$ of the waveguide 10 encounters the

extraordinary refractive index $n_e$ while TE polarized light propagating along the same path encounters the ordinary refractive index $n_o$. This complementary relationship between the vertically and horizontally poled cladding regions may be utilized in a variety of embodiments of the present invention to create polarization-independent integrated optical devices, one of which is illustrated in Fig. 10, discussed below.

It is noted that a non-electrooptic outer optical cladding layer may be defined about a periphery of the core 20, between the first cladding region 22 and the core 20 and the second cladding region 24 and the core 20. It is further noted that the first and second cladding regions 22, 24 may cooperate to enclose the entire periphery of the core 20, as opposed to merely bounding the left and right sides of the core 20. The cladding regions are preferably formed of the same material to help ensure they exhibit equivalent optical and electrooptical properties.

Alternative Electrooptic Clad Waveguide.

Referring now to Fig. 5, an alternative electrooptic clad waveguide arrangement is illustrated. The embodiment of Fig. 5 differs from that illustrated in Figs. 1 and 2 in that the first and second cladding regions 22, 24 of Fig. 5 are poled in perpendicular directions, as opposed to opposite parallel directions. Also illustrated in Fig. 5 is a representation of the optical wave intensity contour TE, TM of the propagating optical signal. The control electrodes 30 are arranged to provide appropriate poling orientations and to ensure that the electric field created in the first cladding region 22 is substantially perpendicular to the electric field created in said second cladding region 24. It is contemplated that alternative control electrode arrangements will also be well suited for the illustrated embodiment.

The waveguide of Fig. 5 achieves polarization-independent single channel phase shifting or modulation through the independently poled cladding regions 22, 24, which optimize phase shifting of one dominant polarization (TE) in the first cladding region 22 and the other dominant polarization (TM) in the second cladding region 24. The embodiment of Fig. 5 may be represented in a beam-propagation modeling tool to verify polarization independence. The beam-propagation modeling tool may also be used to determine alternative control electrode arrangements. Parameters used in the beam propagation modeling for the illustrated embodiment are as follows:

| | |
|---|---|
| Electrode gap, g | 20 μm |
| Electrooptic coefficient (parallel optic and electric field), $r_{PP}$ | 60 pm/V |
| Electrooptic coefficient (perpendicular optic and electric field), $r_{1P}$ | 20 pm/V |
| Substrate index, $n_0$ (fused silica) | 1.44409 |
| Wavelength of optical signal, $\lambda_0$ | 1.55 μm |
| Waveguide core height | 8 μm |
| Index difference between core and cladding | 0.35% |

Single Channel Phase Shifter or Modulator.

Fig. 6 represents a further example of a polarization-independent single channel phase shifter or modulator and illustrates contoured poling as opposed to the horizontal and vertical poling of the embodiments illustrated in Figs. 1-5. Specifically, in the arrangement of Fig. 6, the control electrodes 30 and a dielectric medium 45 are arranged to create a contoured electric field E in the non-electrooptic core 20 and the first and second cladding regions 22, 24. This electric field E may be used to pole the first and second cladding regions 22, 24, in which case, the poling of the first and second cladding regions 22, 24 may be contoured in the same direction as the electric field E.

The control electrodes 30 are also used to initiate the electrooptic modification of the refractive indices of the first and second cladding regions 22, 24, as described above with reference to Figs. 1-5. The dielectric medium 45 is typically provided on a surface of the waveguide 10 opposite the surface upon which the control electrodes 30 are disposed, as is illustrated in Fig. 6. Preferably, the cladding regions 22, 24 are at least partially disposed between the first and second control electrodes 30 and the dielectric constant medium 45. As is described in further detail herein, the contoured electric field E and the respective directions of polarization in the first and second cladding regions 22, 24 define a polarization-independent waveguide structure along the primary axis of propagation of the electrooptic clad waveguide 10. It is contemplated that additional control electrodes 30 may be provided to further tailor the profile and orientation of the electric field E.

The dielectric medium 45 can have a significant effect on the contour of the electric field E. Specifically, the contour of the electric field E may be made more vertical

in the cladding regions 22, 24 by increasing the dielectric constant of the dielectric medium 45. Conversely, the contour of the electric field E may be made more horizontal in the cladding regions 22, 24 by decreasing the dielectric constant of the dielectric medium 45. The distance between the dielectric medium 45 and the control electrodes 30 will also have an effect on the contour of the electric field E. The contoured electric field E is substantially symmetric and is defined by substantially equivalent $x$ and $y$ components in an $x$-$y$ plane defined by the $x$ and $y$ axes. Stated differently, the vertical and horizontal components of the contoured electric field E are balanced in each of the cladding regions 22, 24. In this manner, the $x$ and $y$ components in each of the cladding regions 22, 24 define substantially equivalent phase control of respective TE and TM modes of propagation of an optical signal propagating along the primary axis of propagation $z$ and enable substantially equivalent phase modification of the TE and TM modes of the optical signal.

As will be appreciated by those practicing the present invention, the cladding regions 22, 24 are poled by what may be described as a thermo/electric poling arrangement because the poling is controlled by increasing the temperature of the device, or at least the regions to be poled, imposing the contoured electric field E, and then cooling the device to room temperature with the field still applied. As is illustrated in Fig. 6, the thermo/electric poling arrangement of the present invention is arranged to orient independently the respective polar axes of the cladding regions.

In certain contexts it may be desirable to use electrooptic or otherwise functional waveguide materials in addition to electrooptic cladding regions. To accomplish this objective, the channel waveguides may be constructed of a ferroelectric material, e.g., a crystalline ferroelectric oxide, having a Curie temperature that is greater than the processing temperature of the thermo/electric poling arrangement.

Alternatives in contoured poling

Referring to Figs. 7 and 8, an electrooptic waveguide 110 is illustrated including first and second control electrodes 120, 122, and an optical waveguide core 130. An intersecting plane 132 normal to the surface of the waveguide core 130 and extending along the primary axis of propagation defined by the waveguide core 130 is also illustrated. For the purposes of describing and defining the present invention, it is noted

that TE and TM polarized light represent two independent electromagnetic modes of an optical signal. The electromagnetic field distribution is referred to as the transverse electric (TE) mode where the electric field of the optical signal is perpendicular to the intersecting plane 132. The electromagnetic field distribution is referred to as the transverse magnetic (TM) mode where the magnetic field of the optical signal is perpendicular to the intersecting plane 132. It is also noted that in a channel waveguide of the illustrated type, the propagating modes are not purely TE or TM polarized. Rather, the modes are typically more predominantly one or the other and are commonly so designated.

Accordingly, a TE polarized mode may merely comprise a distribution where the electric field component parallel to the plane of propagation is the largest component of the signal. Similarly, a TM polarized mode may merely comprise a distribution where the magnetic field component parallel to the plane of propagation is the largest component of the signal.

Although a number of alternative waveguide configurations are contemplated by the present invention, many of the general principles of the present invention may be described with reference to the waveguide configurations of Figs. 7 and 8. Alternative waveguide configurations are illustrated schematically in Figs. 9-16, 18, and 19 and are discussed in further detail below.

Referring initially to Figs. 7 and 8, an electrooptic waveguide 110 according to one embodiment of the present invention is illustrated. The waveguide 110 comprises first and second control electrodes 120, 122, an optical waveguide core 130, and a cladding 140 optically coupled to the optical waveguide core 130. The cladding 140 is delineated into first and second lateral cladding regions 142, 144 and a bottom cladding region 146 for illustrative purposes. The delineated cladding regions 142, 144, 146 and the remaining cladding areas within the cladding 140 may be formed of like or different materials, depending upon the desired operational characteristics of the cladding 140 and the waveguide 110. A silica superstrate 150 and a silicon substrate 160, which are merely partially illustrated in Figs. 7 and 8, typically form the respective top and bottom surfaces of the waveguide 110. The optical waveguide core 130 may comprise an electrooptic polymer, silica, or doped silica. Similarly, the cladding 140 may comprise an electrooptic polymer, silica, or doped silica and may include different materials in different regions thereof. For example, the first and second lateral cladding regions 142, 144 may comprise an electrooptic polymer while the bottom cladding region 146 may comprise silica.

The refractive index of the optical waveguide core 130 is slightly higher than that of the surrounding cladding 140. As a result, the waveguide 110 is well suited for guiding an optical signal. According to one embodiment of the present invention, a doped silica waveguide core 130 is envisioned with a refractive index that is 0.7% higher than the silica bottom cladding region 146. This provides good confinement, yet allows some of the light to propagate in the cladding regions 142, 144, 146. If the index difference between the core 130 and cladding 140 is reduced to 0.35%, the optical signal will be more loosely confined and more of the light will propagate in the cladding 140. For a configuration with a passive waveguide core 130 and an electrooptic cladding 140, more efficient electrooptic interaction will occur with the lower index difference. It is further noted that index differences between 0.3% and 1% are better-suited for construction of waveguides that are not susceptible to optical losses from slight bends in the waveguide.

The present invention is particularly advantageous in the context of guiding non-polarized light, i.e., optical signals including both a horizontally oriented component TE and a vertically oriented component TM. Specifically, the optical waveguides described in clued electrode arrangements and poling configurations that provide for electrooptic responses that are insensitive to the polarization of the optical signal with or without a driving voltage applied to the electrodes.

The waveguide 110 of the present invention is configured such that at least a portion of the cross section 112 of an optical signal propagating through the waveguide 110 along the longitudinal direction of the core 130 lies in an electrooptic material. The electrooptic material may be presented as part or all of the cladding 140, as part or all of the core 130, or as a combination thereof. For the purposes of describing and defining the present invention it is noted that electrooptic materials and substantially non-electrooptic materials may be distinguished based on the relative degree of variation in the refractive index induced in the material upon application of an electric field in the material. Electrooptic materials and non-electrooptic materials placed under similar electric fields undergo changes in refractive indices that are typically different by several orders of magnitude. As such, it is contemplated that, even though many materials utilized in optical waveguides exhibit very small changes in refractive index under the influence of an electric field, the difference between electrooptic and non-electrooptic materials will be readily apparent to those practicing the present invention.

Preferably, the electrooptic material comprises an electrooptic polymer. In

electrooptic polymers, the electrooptic effect arises when originally randomly oriented chromophores with relatively large molecular hyperpolarizabilities are oriented along a common direction or contour - a process commonly known as poling. Typically, a polymer is poled by application of an electric field between two or more electrodes across the polymer. The polymer may be poled in any direction or along any contour by utilizing the electric field to align the chromophores in the poling process. According to the present invention, electrooptic polymers are poled in selected contours to provide polarization-independent behavior. The aggregate of directions in which the polymer is poled at each point within it is referred to herein as the poling contour.

This embodiment of thepresent invention also contemplates the use of any other electrooptic materials that can be poled in a contour. For the purposes of defining and describing this embodiment of the present invention, it is noted that a contour generally comprises a curved line but may include straight and curved portions.

In Figs. 7 and 8, the control electrodes 120, 122 are positioned to generate a contoured electric field across the cladding 140. In Fig. 7, the contoured electric field is illustrated with reference to equipotential lines 128. In Fig. 8, the contoured electric field is illustrated with reference to contour lines 126 and equipotential lines 128. The equipotential lines 128 in Figs. 7 and 8 illustrate the magnitude and direction of the electric field. The magnitude of the electric field is represented by the spacing of the equipotential lines 128, where a closer spacing represents a higher magnitude. The direction of the electric field in any given point along one of the equipotential lines 128 is perpendicular to the tangent of the line at the given point and is illustrated with particularity by the contour lines 126 of Fig. 8.

The cladding 140 is poled along the contour defined by the electric field and, as such, the refractive index of the cladding 140 varies with position throughout the cladding 140. Accordingly, the cladding 140 defines an array of local TM indices of refraction $n_{TM}$ corresponding to the indices of refraction for the vertically oriented component TM of the optical signal in the cladding 140. The cladding 140 also defines an array of local TE indices of refraction $n_{TE}$ corresponding to the indices of refraction for the horizontally oriented component TE of the optical signal in the cladding 140. The local TM indices $n_{TM}$ collectively define the TM mode index of the waveguide 110 and the local TE indices $n_{TE}$ collectively define the TE mode index of the waveguide 110.

The local TM indices $n_{TM}$ and the local TE indices $n_{TE}$ are each a function of a first electrooptic coefficient $r_{PP}$ for light parallel to a local component of the contoured electric field and a second electrooptic coefficient $r_{IP}$ for light perpendicular to a local component of the contoured electric field. Other electrooptic coefficients may also characterize the electrooptic material but $r_{PP}$ and $r_{IP}$ are the two dominant coefficients. The difference between the first and second electrooptic coefficients $r_{PP}$ and $r_{IP}$ defines the optical birefringence of the electrooptic cladding material defining the cladding 140.

As is noted above, referring to the equipotential lines of Figs. 7 and 8, the direction of the electric field at any given point along one of the equipotential lines is perpendicular to the tangent of the equipotential line at the given point. Accordingly, the poling contour of the polymer is also illustrated herein by reference to the equipotential lines of Figs. 7 and 8 because the direction of the electric field also defines the direction in which the polymeric chromophores are oriented. The contoured electric field and the poling contour are configured to compensate for the optical birefringence of the electrooptic cladding material such that the TM mode index of the waveguide is substantially equal to the TE mode index of the waveguide. In this manner, the output of the optical waveguide 110 may be controlled independent of the polarization of the input optical signal. In cases where the waveguide 110 is silica-based glass, it will be preferable to select an electrooptic cladding material having a dielectric constant on the order of about 3.6, or some other relatively low dielectric constant, to avoid distortion of the electric field by the electrooptic material.

In the embodiments of Figs 7 and 8, the contoured electric field and the poling contour are asymmetric relative to an intersecting plane 132 normal to the surface of the waveguide core 130 and extending along the primary axis of propagation defined by the waveguide core 130. Generally, the contour of the electric field and the poling lines are such that (i) the vertical electric field component within the first lateral cladding region 142 is larger than a vertical electric field component in second lateral cladding region 144 and (ii) the horizontal electric field component within the first lateral cladding region 142 is smaller than the horizontal component in the second lateral cladding region 144. Figs. 17-19 illustrate respective primary axes of propagation 135 for selected waveguide cores 130.

Typically, as is the case in the embodiments of Figs. 7 and 8, the contoured electric

field and the poling contour lie along a common contour because the same control electrodes 120, 122 are used to pole the electrooptic material and to drive the waveguide 110. However, it is contemplated that the poling lines and electric field need not follow a common contour. It is further contemplated that a suitably contoured electric field may be employed with an electrooptic material that is poled in a linear, uniform fashion or that a linear, uniform electric field may be employed with an electrooptic material poled along a suitable contour.

The poling voltage is selected to achieve optimum polarization of the electrooptic material and varies depending upon the dimensions and properties of the electrooptic material. The driving voltage, which is typically much less than the poling voltage, is selected to achieve a polarization-independent $\pi$ phase shift in the optical signal. Typical driving electric fields are in the range of about 1 V/μm to about 10 V/μm. For convenience of operation, the driving voltage and the poling voltage may have the same polarity and thus be co-directional. However, according to one embodiment of the present invention, the poling voltage and driving voltage can be opposite in polarity. Specifically, the poling voltage and the driving voltage applied to the control electrodes may be poled such that contra-directional electric fields are created in the cladding.

Generally, control electrodes utilized according to the present invention may be constructed of any suitable conductive or superconductive material and may be provided in thicknesses ranging from a few hundred angstroms to about 10 μm. In arranging the control electrodes of the present invention, care should be taken to ensure adequate spacing between the electrodes and areas of the device 110 carrying an optical signal. Preferably, the control electrodes of the present invention should be spaced about 1 μm to about 10 μm from the optical signal. If the electrodes are placed too close to the optical signals, significant optical attenuation will result. Alternatively, optically transparent electrodes such as indium tin oxide (ITO) can be used to produce the electric field. Optically transparent electrodes will not significantly reduce the optical signal in a nearby waveguide if they are appropriately designed.

A controller may be coupled to the control electrodes to enable proper control of the voltages applied thereto. The controller is merely illustrated schematically herein by reference to voltages $V_1$, $V_2$, and $V_3$ (see Figs. 9-16). The controller is preferably programmed to operate the control electrodes at suitable poling and driving voltages but manual control is also contemplated.

Figs. 7-16, 18, and 19 of the present application illustrate a variety of control electrode and core configurations suitable for achieving polarization independence according to the present invention. As will be appreciated by those practicing the present invention, the illustrated embodiments are not intended to present an exhaustive disclosure of all of the possible electrode and core configurations within the scope of the present invention. The appended claims also relate to a variety of configurations according to the present invention and the terms and phrases utilized therein take their meaning from the detailed description of the embodiments of Figs. 7-16, 18, and 19. Accordingly, we turn now to a detailed description of the configurations illustrated in Figs. 7-16, 18 and 19.

In Fig. 7, the first and second control electrodes 120, 122 are bound by a common edge plane at the interface between the cladding 140 and the superstrate 150 but define an asymmetric configuration. For the purposes of defining and describing the present invention, this common edge plane will be referred to herein as the common edge plane. In addition, the second control electrode 122 defines an electrode thickness dimension that is substantially less than the corresponding electrode thickness of the thicker remaining control electrode 120. The core 130 is positioned equidistant between the control electrodes (see Fig. 7). For the purposes of describing and defining the present invention, where a structural element defines a substantially uniform shape, like the quadrilaterals illustrated herein, a distance between two elements represents the distance between the closest points of the two elements, as opposed to the distance between the respective centroids of the two elements. However, where structures define irregular or non-uniform shapes it may be preferable to establish the distance between two elements as the distance between the centroids of the elements or to approximate the shapes of the non-uniform elements as uniform shapes.

In Fig. 8, the arrangement of the control electrodes 120, 122 is similar to that of Fig. 7 but the core 130 is offset from the common edge plane in which the electrodes lie. Further, the core 130 is positioned unequal distances from the control electrodes 120, 122, closer to the thinner control electrode 122. The core 130 may be positioned closer to the thicker control electrode 120 in Fig. 7 or Fig. 8, as long as the result is a configuration where the TM mode index of the waveguide 110 is substantially equal to the TE mode index of the waveguide 110. By way of example, the following parameters may apply to the arrangement of Fig. 8:

| | |
|---|---|
| Poling Voltage: 1500 V (100V/μm) | Dielectric Constant Of Electrooptic Cladding: 2.25 |
| Electrode Dimensions: 9 μm x 10 μm; 1 μm x 10 μm | Refractive Index of Cladding at 1550 nm: 1.444 |
| Free Space Wavelength: 1550 nm | Electrode Separation: 15 μm |
| Refractive Index of Doped Silica Core: 1.4542 | Core Position: 3 μm below top surface of electrodes<br>6.75 μm right of center |
| Core Height and Width: 8 μm x 3 μm | Electrooptic Coefficients: $r_{PP}$ = 60 pm/V; $r_{IP}$ = 20 pm/V |

Before moving on to a discussion of the alternative configurations illustrated in Figs. 9-16, 18, and 19, we turn to a detailed explanation of the manner in which polarization independence is achieved according to the present invention. Initially, we note that the process of poling the electrooptic material of the waveguide 110 orients the chromophores and locks them in place. As a result, the electrooptic material becomes anisotropic because, even without an electric field applied, the refractive index of the electrooptic material will depend on the orientation of the optical polarization. Once a driving voltage is applied to the control electrodes 120, 122 and a driving electric field is induced, the refractive indices will change further due to the electrooptic effect.

Once the electrooptic polymer is poled, the calculation of the optical propagation of the waveguide must account for the positional variation of the electric field and the refractive index of the waveguide 110. The calculation must also account for the fact that the evanescent tail of the optical signal falls off exponentially from the waveguide edge, as is illustrated by the cross section of the optical signal 112 in figs. 7 and 8. As a result, regions very close to the waveguide core 130 have more influence on the optical signal than materials a few microns away from the waveguide. Typically, for example, the height and width dimensions of the core 130 will vary from 2μm to 8μm where a 3x8 μm core having the illustrated orientation is preferred. The dimensions of the core 130 will typically increase as the difference between the indices of the core and cladding become smaller.

The calculation of the optical propagation of the waveguide must also take into account the electrooptic coefficient of the electrooptic material. Fortunately, although the electroöptic coefficient will also vary with position when the poling fields are not sufficient to completely pole the polymer, it is possible to render the degree of poling variation insignificant to the calculation. To do this, poling fields of sufficient magnitude and duration should be used to pole the polymer as completely as possible near the waveguide core 130. In practice, electrooptic coefficients on the order of between about 1pm/V and 200 pm/V and electric fields in excess of 100 V/μm are preferred. It is contemplated that an accurate determination of suitable poling voltage characteristics for completely poling the electrooptic material near the waveguide core 30 will depend upon the dimensions and properties of the various waveguide components and are best left to experimental determination.

The respective TM and TE mode indices may be calculated using a software model incorporating: 1) a calculation of the electric field contours within the electrooptic material; 2) a calculation of the birefringence of the waveguide resulting from the poling process; and 3) a calculation of the electrooptically induced change in refractive index of the waveguide. The electric field contours in the device are calculated using a finite element model that incorporates the electrode geometry and the dielectric constants of the cladding 140 and core 130 materials. As will be appreciated by those familiar with finite element analysis, the finite element model divides the problem space into a finite number of elements having a selected size, e.g., 0.5 μm by 0.5 μm.

During the poling process, the chromophores within the electrooptic material are aligned and the refractive index becomes polarization dependent, or birefringent. The amount of local birefringence at any specific point in the electrooptic material can be determined from the strength and direction of the electric field and the material properties. Since the electric field forms a contour and varies in both magnitude and direction throughout the electrooptic material, a coordinate transformation should be used to determine the amount of local birefringence at any specific point in the electrooptic material relative to the horizontal and vertical axes. The details of the coordinate transformation may be derived from conventional planar geometry. Similarly, the manner in which optical birefringence of a material may be calculated from the dominant electrooptic coefficients of the material and the applied electric field may be determined from conventional teachings in the area of electrooptic waveguide devices. For common

electrooptic polymers, a field of 100 V/μm will induce a birefringence of 0.003. This means that the refractive index of the material as seen by light polarized in the direction of the electric field will be larger than the index seen by light polarized perpendicular to the electric field by 0.003.

Once the local birefringence is determined for each element in a 0.5 μm by 0.5 μm grid, the overall waveguide birefringence can be determined using an optical beam-propagation model. The mode index for each polarization is treated separately. The difference between the TM and TE mode indices is the waveguide birefringence.

To calculate the electrooptically-induced change in refractive index, the electrooptic material is again divided into finite elements of constant index. The refractive index is then calculated as a function of voltage for both TE and TM polarized light and each element may be characterized by a refractive index associated with the horizontal axis (and thus TE polarization) and a refractive index associated with the vertical axis (and thus TM polarization). This array of refractive indices is then provided as input to an optical beam propagation model that calculates the propagation of an optical signal through this array of indices. Finally, a doped-silica waveguide is placed within the refractive index array and the propagation characteristics of the waveguide are determined using beam propagation modeling software. The calculation is carried out twice, once for TM polarized light (with the vertical index array) and once for TE polarized light (with the horizontal index array).

Referring now to Fig. 9, a configuration is illustrated wherein the control electrodes 120, 122 define an asymmetric configuration, lie in a common edge plane, and define substantially equal electrode thickness dimensions. The core 130 is offset from the common edge plane and is positioned closer to the second control electrode 122. It is contemplated that polarization-independent operation could also be achieved if the electrodes 120, 122 were symmetric or if the core 130 were placed closer to the first control electrode 120. Such modifications would often necessitate corresponding changes to the configuration of another electrical, optical, or electrooptical element of the waveguide.

In the embodiment of Fig. 10, first, second, and third electrodes 120, 122, 124 are symmetrically arranged in a common edge plane. Each of the electrodes define substantially equal thicknesses. The core 130 is offset from the axis of symmetry of the control electrodes 120, 122, 124 and from the common edge plane. In Fig. 11, the

thickness of the first electrode 20 exceeds that of the remaining two electrodes. In Fig. 12, the second electrode 122 is substantially thinner than the remaining two electrodes 122, 124 and the core is positioned closer to the first control electrode 120. Possible variations to the arrangements illustrated in Figs. 10-12 include, but are not limited to: modification of the electrode structure from symmetric to asymmetric, or from asymmetric to symmetric, modification of the thickness of one or more of the electrodes, elimination of an electrode, repositioning of the core closer to a selected electrode, etc. Of course, such modifications would often necessitate corresponding changes to the configuration of another electrical, optical, or electrooptical element of the waveguide.

In the embodiments of the present invention where two control electrodes are utilized, one of the electrodes is at a positive voltage and the other of the control electrodes is at ground or a suitable negative voltage. The arrangements of Figs. 10, 11, and 12, and some of the embodiments discussed below, include provision for three control electrodes. Each of the three electrodes may be operated at different voltages. However, it is more typical to operate two of the electrodes at a common voltage and select a third electrode for operation at a higher or lower voltage. Specifically, in Figs. 10-12, the first and third electrodes 120, 124 are typically operated at a relatively high positive voltage $V_1$, $V_3$ while the second electrode 122 is operated at a lower voltage $V_2$. In Figs. 15 and 16, discussed in further detail below, the first and second electrodes 120, 122 are typically operated at a relatively high positive voltage $V_1$, $V_2$ while the third electrode 124 is operated at a lower voltage $V_2$. Of course, it is contemplated that the polarity of the voltage examples recited with reference to Figs. 10-12 and 15-16 could be reversed to arrive at the same effect.

The embodiments of Figs. 13-16 contemplate symmetric or asymmetric electrode arrangements where the waveguide comprises first and second control electrodes 120, 122 lying in parallel planes and the core 130 is positioned between the parallel planes. The embodiments of Figs. 15 and 16 include a third control electrode 124. In each of these embodiments, the first control electrode 120 is limited to extend for a majority of its width along one side of the core 130 and the second control electrode 122 is limited to extend for a majority of its width along the other side of the core 130. Further, in each case, the core 130 is positioned unequal distances from the control electrodes 120, 122, 124. As is noted above, possible variations to the arrangements illustrated in Figs. 13-16 include, but are not limited to: modification of the electrode structure from symmetric to asymmetric, or from asymmetric to symmetric, modification of the thickness of one or more of the

electrodes, elimination of an electrode, repositioning of the core closer to a selected electrode, etc. Of course, such modifications would often necessitate corresponding changes to the configuration of another electrical, optical, or electrooptical element of the waveguide.

Referring now to Figs. 17-19, respective primary axes of propagation 135 and the relative length dimensions of the control electrodes along the axes 135 are illustrated. Specifically, referring to Fig. 17, the first and second control electrodes 120 and 122 are illustrated with substantially equal length dimensions that extend for substantially the entire length of the waveguide core 130. Similarly, in Fig. 18, the first, second, and third control electrodes 120, 122, 124 each define substantially equal length dimensions that extend for substantially the entire length of the waveguide core 130. Alternatively, as is illustrated in Fig. 19, in the case of an electrode configuration including three or more electrodes, one of the control electrodes 120, 122, 124, e.g., the third control electrode 124, may have a reduced length dimension along the primary axis of propagation 135 of the waveguide core 130. The reduced length of the third control electrode 124 may be selected to provide for further compensation for birefringence resulting from differences between the TM and TE mode indices of the waveguide.

Figs. 20A-20D illustrate a process for forming an electrooptic waveguide according to the present invention. Referring to Fig. 20A, two control electrodes 120, 122 are provided on a first surface 152 of the waveguide superstrate 150. The respective thicknesses of one or both of the electrodes may be selectively increased by forming the electrodes as part of a plating process or any other selective formation process (see Fig. 20B). Similarly, the optical waveguide core 130 is provided over a first surface 162 of the waveguide substrate 160. Next, a viscous electrooptic cladding material 140 is provided over the first surface 162 of the substrate 160, which may include a cladding region 146. The viscous cladding material 140 may also be provided over the first surface 152 of the superstrate 150, or both (see Fig. 20C). Finally, the surfaces 152, 162 are urged toward each other to create a structure having a layer of cladding material interposed between the surfaces 152, 162. Finally, the cladding material 140 is cured, yielding a unitary waveguide structure 110 (see Fig. 20D).

The cladding material 140 defines a cladding material viscosity selected to permit dispersion of the cladding material 140 about the control electrodes 120, 122 and the core 130 as the first surface 162 of the waveguide substrate 160 and the first surface 152 of the

waveguide superstrate 150 are urged toward each other. As is illustrated in Fig. 20D, the cladding material 140 is provided in a quantity sufficient to ensure that the layer of cladding material 140 defines a cladding layer thickness at least as large as the selected electrode thicknesses.

Variations to the manufacturing scheme illustrated in Figs. 20A-20D are illustrated in Figs. 18 and 19. Specifically, it is noted that the control electrodes 120, 122 may be formed over an intervening material 170 that is formed over the superstrate 150. This approach adds additional flexibility in positioning the control electrodes relative to the core 130 and each other. Further, this approach can reduce material costs if the intervening material is less expensive than the electrode material.

Phase-Modulating Integrated Optical Device.

Figs. 23-25 illustrate a further arrangement for a phase-modulating integrated optical device according to the present invention. In the arrangement of Figs. 23 and 24, the control electrodes 30 are positioned adjacent the first and second cladding regions 22, 24, in generally the same plane as the waveguide core 20. Fig. 24 illustrates a computed transverse mode profile I of an optical signal propagating along the waveguide 10. According to one aspect of the present invention illustrated in Fig. 25, the transverse dimension or width of the waveguide core 20 is "thinned-down." Specifically, the cross-sectional $x$ axis width of the core 20 decreases from a region outside of the first and second cladding regions 22, 24 to a region bounded by the first and second cladding regions 22, 24. Optimum device design may be achieved by placing a greater portion of the optical energy of the signal in the cladding regions 22, 24.

The following table illustrates the influence of the cladding index $\Delta n_{clad}$ on the effective index $\Delta n_{eff}$ of the waveguide for three different core widths.

| Core Width | $\Delta\Phi/\Delta n_{clad}$ | $\Delta n_{eff}/\Delta n_{clad}$ |
|---|---|---|
| 3μm | -16.7 x $10^3$ radians | 0.441 |
| 5μm | -7.88 x $10^3$ radians | 0.194 |
| 7μm | -4.19 x $10^3$ radians | 0.103 |

The electrooptic clad waveguide is characterized by an optical phase delay $\Phi=2\pi L n_{eff}/\lambda$, where $n_{eff}$ is the effective index of refraction of the waveguide, $\lambda$ is the wavelength of light propagating along the optical path, and $L$ is the length over which the phase delay occurs. The data show that with proper design of the waveguide core 20, the cladding index $\Delta n_{clad}$ can have a strong influence on the effective index $\Delta n_{eff}$ of the waveguide 10. Specifically, for the 3μm core 20, the change in the effective index $\Delta n_{eff}$ of the waveguide 10 is about 45% of the value of the change in the cladding index $\Delta n_{clad}$. The change in the effective index $\Delta n_{eff}$ of the waveguide 10 can be described as being core independent because the core is substantially non-electrooptic. The first and second control electrodes 30 merely create an electric field in the first and second cladding regions capable of changing the refractive indices of the first and second electrooptic cladding regions 22, 24 without a corresponding change in the refractive index $n_1$ of the waveguide core 20.

Preferably, the cross-sectional $x$ axis width of the core 20, decreases by about 40-60 %. In preferred embodiments of the present invention, the cross-sectional $x$ axis decreases in width from about 5-8μm in the region outside of the first and second cladding regions to about 3μm in the region bounded by the first and second cladding regions.

Intensity Modulator or 2x2 Polarization-Independent Optical Switch.

Referring now to Fig. 26, an integrated optical device 5 according to the present invention is illustrated. The optical device 5 may take the form of an intensity modulator or a 2x2 polarization-independent optical switch. The optical device 5 comprises first and second waveguides 10A, 10B arranged to define a Mach-Zehnder interferometer. Generally, the Mach-Zehnder interferometer comprises an electrooptically controlled phase shifter along each of the first and second waveguides 10A, 10B, a beam splitter 12 at the input side of the interferometer and a beam combiner 14 at the output side of the interferometer. The optical signal output $I_{out}$ at each waveguide 10A, 10B may be controlled by varying the relative phase difference across both of the waveguides 10A, 10B to alter the interference at the combiner 14.

The arrangement illustrated in Fig. 26 includes first and second directional coupling regions in the form of a beam splitter 12 and a beam combiner 14, an intermediate coupling region 16 disposed between the first and second directional

coupling regions 12, 14 and a set of control electrodes 30. The first and second cladding regions 22A, 24A, 22B, 24B may be poled in opposite directions, in perpendicular directions, or in substantially the same direction, as is described above with reference to Figs. 1-6. Further, the waveguide cores 20A, 20B may define a cross-sectional $x$ axis width that decreases in the manner described above.

In the context of an intensity modulator, the device is provided with an optical input 32A and a pair of optical outputs 34A, 34B. At least one of the first and second waveguides 10A, 10B comprises a phase shifter in the form of an electrooptic clad waveguide according to the present invention. The non-electrooptic optical waveguide cores 20A, 20B define a refractive index $n_1$ and are disposed between first and second cladding regions 22A, 24A, 22B, 24B in the intermediate coupling region 16. Each of the cladding regions 22A, 24A, 22B, 24B comprises a poled electrooptic polymer defining a refractive index that is less than $n_1$.

The control electrodes 30 are arranged to create an electric field in the first and second cladding regions 22A, 24A, 22B, 24B. The electric field changes the refractive indices of the first and second electrooptic cladding regions 22A, 24A, 22B, 24B to induce a change in the effective index of refraction $n_{eff}$ of the electrooptic clad waveguides 10A, 10B. As is described above, an optical phase delay $\Phi$ is introduced in the waveguides 10A, 10B due to the change in the effective index of refraction $n_{eff}$ of the waveguide 10A, 10B, i.e., $\Phi=2\pi L n_{eff}/\lambda$.

Preferably, as is noted above with reference to Figs. 1-4, the control electrodes 30 are arranged such that a quantitative combination of the electric field and the poling in the first cladding regions 22A is substantially equivalent to a quantitative combination of the electric field and the poling in the second cladding region 24A. Similarly, a quantitative combination of the electric field and the poling in the first cladding regions 22B is substantially equivalent to a quantitative combination of the electric field and the poling in the second cladding region 24B.

If the two directional coupling regions 12, 14 are set as 50% beam splitters, then the optical output intensity $I_{out}$ at the optical outputs 34A, 34B are related to the optical input intensity $I_{in}$ according to the following equations

$$|I_{out}|^2 = |I_{in}|^2 \sin^2\left(\frac{\phi}{2}\right)$$

$$|I_{out}|^2 = |I_{in}|^2 \cos^2\left(\frac{\phi}{2}\right)$$

where $\Phi$ represents optical phase difference across both waveguides 10A, 10B resulting from the change in the effective index of refraction $n_{eff}$ in each electrooptic clad waveguide 10A, 10B. Thus, by controlling the voltage across the control electrodes 30, the arrangement illustrated in Fig. 26 may be utilized to modulate the optical intensity at the optical outputs 34A, 34B.

The arrangement illustrated in Fig. 26 may also be utilized to operate as a 2x2 polarization-independent optical switch. Specifically, where separate optical signals are provided at the first and second optical inputs 32A, 32B the control electrodes 30 can be arranged to create an electric field in the first and second cladding regions 22A, 24A, 22B, 24B of the first and second waveguides 10 to induce a change in an effective index of refraction $n_{eff}$ of the first and second waveguides 10A, 10B. In this manner, input optical signals may be directed selectively to separate ones of the optical outputs 34A, 34B by controlling the electric field applied to the first and second cladding regions 22A, 24A, 22B, 24B of the first and second waveguides 10.

To ensure polarization independence, the poling of the first and second cladding regions 22A, 24A of the first waveguide 10A is substantially perpendicular to the poling of the first and second cladding regions 22B, 24B of the second waveguide 10B. In this manner, the polarization of an input optical signal is of no concern to the effectiveness of the 2x2 switch because, each waveguide 10A, 10B is configured to modulate a selected polarization more than another. In the illustrated embodiment, the waveguide 10A will modulate TE polarized light significantly more than TM polarized light but the waveguide 10B will modulate TM polarized light more than TE polarized light by roughly the same relative proportions. Accordingly, TE and TM polarized light propagating along the first and second waveguides 10A, 10B are phase modulated to different degrees in each of the waveguides but to substantially equal degrees across both of the waveguides, yielding a polarization-independent optical device.

High-frequency Modulator.

Referring now to Fig. 27, an integrated optical device 5 according to the present invention is illustrated. The optical device 5 is similar to that illustrated in Fig. 26 but takes the form of a high-frequency modulator. Specifically, the device 5 comprises first and second waveguides 10A, 10B arranged to define a Mach-Zehnder interferometer including first and second directional coupling regions 12, 14, an intermediate coupling region 16, a set of control electrodes 30 , an optical input 32 , and an optical output 34.

The second waveguide 10B comprises an electrooptic clad waveguide portion, as described above with reference to Figs. 1-6 and 23-26. The control electrodes 30 form a traveling wave stripline 50 and are arranged to create an electric field in the first and second cladding regions 22, 24. As is described above, the electric field changes the refractive indices of the first and second electrooptic cladding regions 22, 24 and induces a change in an effective index of refraction $n_{eff}$ of the electrooptic clad waveguide 10B and a corresponding phase shift $\Phi$ in the optical signal. As will be appreciated by those practicing the present invention, a traveling wave stripline comprises a strip transmission line that includes a center conductor separated from outer conductors by dielectric strips.

The traveling wave stripline 50 utilized in the illustrated embodiment of the present invention comprises a microwave input port 52 and a 50Ω termination 54 and is characterized by a dielectric constant ε at microwave frequencies. The dielectric constant ε is selected such that an optical signal propagating in the electrooptic clad waveguide 10B propagates at the same velocity as an electrical signal propagating in the traveling wave stripline 50. Typically, the integrated optical device is configured such that $\varepsilon = \left(n_{eff}\right)^2$. Velocity matching of the electrical and optical signals is often more easily achieved using low dielectric constant materials such as polymers and glass.

Wavelength-dependent Optical Switch.

A wavelength-dependent optical switch according to the present invention is illustrated schematically in Fig. 28. The optical device 5 is similar to that illustrated in Fig. 26 with the exception that the optical path length of the second electrooptic clad waveguide 10B is reduced, relative to the first electrooptic clad waveguide 10A - forming what is referred to as an asymmetric Mach-Zehnder interferometer. As is the case in the embodiment illustrated in Fig. 10, to ensure polarization-independent operation, the poling

of the first and second cladding regions 22A, 24A of the first waveguide 10A is substantially perpendicular to the poling of the first and second cladding regions 22B, 24B of the second waveguide 10B.

First and second wavelength components $\lambda_1$, $\lambda_2$ of an optical signal at input 32A may be directed selectively to separate ones of the optical outputs 34A, 34B by establishing a suitable difference $\Delta L$ between the optical path lengths of the first and second waveguides 10A, 10B and controlling the electric field across the electrooptic cladding regions 22A, 24A, 22B, 24B. Specifically, where the input signal at 32A includes the first and second wavelength components $\lambda_1$, $\lambda_2$, the signals at outputs 34A and 34B will comprise only one of the wavelength components ($\lambda_1$ or $\lambda_2$) for each output 34A, 34B and may be flip-flopped as follows, depending upon the nature of the electric field applied to the control electrodes 30:

| | Input Signal - 32A | Output Signal - 34A | Output Signal - 34B |
|---|---|---|---|
| Normal State | $\lambda_1, \lambda_2$ | $\lambda_1$ | $\lambda_2$ |
| Flip-Flopped | $\lambda_1, \lambda_2$ | $\lambda_2$ | $\lambda_1$ |

The voltage required for proper switching depends upon a number of parameters including the electrooptic coefficient of the polymeric cladding, the interaction length, the waveguide width, etc. The wavelength-dependent switch illustrated in Fig. 28 may be made polarization-independent by poling the cladding regions and arranging the electrodes as taught herein with reference to Fig. 26.

Directional Coupler.

The optical device 5 illustrated schematically in Figs. 29, 30A and 30B comprises a directional coupler including first and second electrooptic clad waveguides 10A, 10B arranged to define a directional coupling region 12, a set of control electrodes 30, first and second optical inputs 32A, 32B, and first and second optical outputs 34A, 34B. The first electrooptic clad waveguide 10A comprises a substantially non-electrooptic optical waveguide core 20A defining a refractive index $n_1$. The waveguide core 20A of the first waveguide is disposed between a first outer electrooptic cladding region 22A and an electrooptic gap region 25 in the directional coupling region 12. The first outer cladding

region 22A comprises a poled electrooptic polymer defining a refractive index that is less than $n_1$. The electrooptic gap region 25 also comprises a poled electrooptic polymer defining a refractive index that is less than $n_1$.

The second electrooptic clad waveguide 10B comprises a substantially non-electrooptic optical waveguide core 20B defining a refractive index $n_1$. The waveguide core 20B of the second waveguide 10B is disposed between a second outer electrooptic cladding region 22B and the electrooptic gap region 25. The second outer cladding region 22B comprises a poled electrooptic polymer defining a refractive index that is less than $n_1$. The control electrodes 30 are arranged to create an electric field across the outer cladding regions 22A, 22B and the electrooptic gap region 25, whereby an optical signal incident in one of the waveguides 10A, 10B may be switched to the other of the waveguides 10A, 10B.

As is noted above, the outer cladding regions or the gap regions may be poled to render the directional coupling region polarization-independent. The amount of light that couples between two optical waveguides depends on the propagation constants of the two waveguides, the distance between the two waveguides, and the length of the interaction region. In the illustrated embodiment, the propagation constant of waveguide core 20A is influenced predominantly by its index of refraction, the index of the outer cladding region 22A, and the index of the gap region 25. Since the outer cladding region 22A and the gap region 25 are electrooptic, the propagation constant is influenced by the applied electric field through the outer cladding region 22A and the gap region 25. In a similar way, the propagation constant of waveguide core 20B is influenced predominantly by its index of refraction, the index of the outer cladding region 22B, and the index of the gap region 25. To achieve polarization-independent coupling, the two polarizations must encounter the same propagation constants.

Referring now to Fig. 30A, a polarization-independent design is illustrated where, with proper placement of the control electrodes 30, the gap region 25 is poled and arranged to predominantly influence TE polarized light and the outer cladding regions 22A, 22B are poled and arranged to predominantly influence the TM polarized light in the respective waveguide cores 20A, 20B.

Fig. 30B shows an alternative to the poling arrangement illustrated in Fig. 30A. A contoured poling arrangement similar to that described herein with reference to Fig. 6 is

illustrated in Fig. 14B. Specifically, in the arrangement of Fig. 30B, the control electrodes 30 and the dielectric medium 45 are arranged to create a contoured electric field E in the non-electrooptic cores 20A and 20B, the first and second electrooptic outer cladding regions 22A and 22 B, and the electrooptic gap region 25. As is described above with reference to the contoured poling arrangement of Fig. 6, the vertical and horizontal components of the contoured electric field E are appropriately arranged in the outer cladding regions 22A, 22B and the gap region 25 to achieve equal coupling for the TE and TM polarizations.

Phase Compensating Element.

Each of the embodiments of the present invention may utilize the thinned-down waveguide core illustrated in Fig. 25 to optimize the effect of the electrooptic cladding regions on the optical signal. However, where a thinned-down core is utilized, it may be necessary to employ a phase compensating element 80 in the manner illustrated in Fig. 33. Specifically, referring to Figs. 31-33, the present applicants have recognized that a width reduction in a fixed height waveguide core creates a phase change difference between the TE and TM modes over a given length of a thinned-down waveguide segment 85. Accordingly, an increased-width phase compensating element 80 according to the present invention is introduced along the optical signal path to compensate for the phase change induced by the reduced-width or thinned-down segment 85. Tapered transitions 82 couple adjacent waveguide portions to the phase compensating element 80 and the thinned-down waveguide segment 85.

Fig. 31 illustrates schematically the relationship of TE and TM modes as an optical signal propagates through a reduced-width waveguide segment. The change in relative velocity of the two modes creates a phase change difference ($\Phi_{TE}$ - $\Phi_{TM}$) over a given waveguide length $L$. The magnitude of the phase change difference varies as a function of the height $h$ of the waveguide core and the length $L$ and width $w$ of the reduced-width segment. Fig. 32 illustrates phase change differences ($\Phi_{TE}$ - $\Phi_{TM}$) per unit length $L$ for a number of different core heights $h$ (5, 6, 7, and 8μm) over a range of widths $w$ (3-12μm).

Referring to Fig. 33, the data of Fig. 32 may be used to design an appropriate compensating waveguide segment 80 according to the present invention. For example, given a square waveguide with a core height $h$ of 5μm and a rectangular reduced-width

core segment with the same height and a reduced-width of 3μm, it may be noted that the reduced-width core segment 85 will introduce a phase change difference of about -35 deg./cm. Accordingly, to compensate for the -35 deg./cm phase change difference the compensating waveguide segment 80 should be designed to introduce a phase change difference of about +35 deg./cm. Given the same core height of 5μm, it may then be noted from the data of Fig. 32 that core width of the compensating waveguide segment should be about 8.5μm to introduce the +35 deg./cm compensation. In the illustrated embodiment, the thinned-down portion defines a length of about 2 cm, the compensating element defines a length that is at least about 2cm, and the tapered transitions define a length of about 0.3 cm.

As is noted above, the phase shift data is presented in Fig. 32 as a function of the length $L$ of the compensating waveguide segment 80. Accordingly, it is also possible to control the compensating phase shift introduced by the compensating waveguide segment 80 by controlling its length $L$. For example, referring to Fig. 33, the above-noted -35 deg./cm phase change difference may be compensated for by (i) utilizing the compensating waveguide segment discussed above, having a core width of about 8.5μm and a length equal to the length of the reduced-width core segment 85 ($L$=2cm) or by (ii) utilizing a compensating waveguide segment having a core width of about 6.5μm and a length twice that of the length of the reduced-width core segment 85 ($L$=4cm). One problem with this approach, however, is that the length $L$ can become too large for the practicalities of device design. Accordingly, preferred parameters compensate for phase shifting while minimizing the length dimension $L$.

It is noted that selected features of the many embodiments described herein may be utilized in other embodiments of the present invention despite the fact that each embodiment description does not reference a particular feature. For example, it is contemplated that each of the embodiments described herein may take advantage of the thinned down waveguide core illustrated in Fig. 25. Further, many of the devices described herein may be rendered polarization-independent by observing the poling illustrated in Fig. 26.

It is also contemplated that the electrooptic cladding regions described herein may be replaced with other optically functional materials having a refractive index that may be controlled in response to a control parameter. Other suitable optically functional materials

include non-linear materials, thermooptic materials, magnetooptic materials, and piezoelectric or electrostrictive materials with appropriate changes in electrode arrangements. For the purposes of defining and describing the present invention, it is noted that these materials are simply referred to herein as optically functional materials. The non-electrooptic analogs of the optically functional materials are referred to herein as optically non-functional materials. As is described above in relation to the electrooptic materials, the capability of independently orienting two or more optically functional cladding material regions provides additional flexibility in device design.

For the purposes of describing and defining the present invention, it is noted that the term "substantially" is utilized herein to represent the inherent degree of uncertainty that may be attributed to any quantitative comparison, value, measurement, or other representation. For example, although certain electric fields are illustrated herein as being perpendicular to each other, it should be appreciated that it would be virtually impossible to ensure that the two fields are exactly perpendicular to each other because there would always a specific degree of uncertainty in the methodology utilized to establish the perpendicular relationship. The term "substantially" is also utilized herein to represent the degree by which the quantitative representation may vary from a stated reference without resulting in a change in the basic function of the subject matter at issue. For example, the optical waveguide core 20 of the present invention is defined herein as being "substantially" non-electrooptic because, although the core may exhibit electrooptic properties under some conditions, the electrooptic properties so exhibited would not result in a material change to the optical signal therein under normal conditions.

The term "symmetric" is utilized herein to represent correspondence in size, shape, and relative position of parts on opposite side of a dividing line or median plane. Where a component is identified as being between two other components or reference planes, it is understood that all or a portion of the component may be between the two other components or reference planes.

Having described the invention in detail and by reference to preferred embodiments thereof, it will be apparent that modifications and variations are possible without departing from the scope of the invention defined in the appended claims. More specifically, although some aspects of the present invention are identified herein as preferred or particularly advantageous, it is contemplated that the present invention is not necessarily limited to these preferred aspects of the invention.

CLAIMS

1. An electrooptic clad waveguide comprising an optical waveguide core defining a primary axis of propagation $z$, a first cladding region offset from said $z$ axis in a first direction along an $x$ axis perpendicular to said $z$ axis, and a second cladding region offset from said $z$ axis in a second direction along said $x$ axis, wherein:

said optical waveguide core comprises a substantially non-electrooptic material defining a refractive index $n_1$;

said first cladding region comprises an electrooptic polymer defining a refractive index that is less than $n_1$;

said second cladding region comprises an electrooptic polymer defining a refractive index that is less than $n_1$; and

said first and second cladding regions are poled in opposite directions.

2. A waveguide as claimed in claim 1 wherein said first and second cladding regions are poled in opposite directions parallel to said $x$-axis.

3. A waveguide as claimed in claim 1 wherein said first and second cladding regions are poled in opposite directions parallel to a $y$-axis perpendicular to said $x$-axis and said $z$ axis

4. A waveguide as claimed in claim 1 wherein:

said electrooptic clad waveguide further comprises first and second control electrodes arranged to create an electric field in said first and second cladding regions; and

said control electrodes are arranged such that a quantitative combination of said electric field and said poling in said first cladding region is substantially equivalent to a quantitative combination of said electric field and said poling in said second cladding region.

5. A waveguide as claimed in claim 4 wherein said quantitative combination of said electric field and said poling is represented by the following equation

$$\Delta n = -\frac{1}{2} n^3 r_{ij} E_j$$

where $r_{ij}$ is the electrooptic coefficient of the cladding region at issue and $E_j$ represents the strength and orientation of the electric field.

6. A waveguide as claimed in claim 1 wherein said first and second cladding regions are separated by about 3 μm.

7. A waveguide as claimed in claim 1 wherein said waveguide core defines a cross-sectional $x$ axis width that decreases from a region outside of said first and second cladding regions to a region bounded by said first and second cladding regions.

8. A waveguide as claimed in claim 1 wherein said optical waveguide core comprises a doped silica waveguide and said refractive index $n_1$ is about 1.45 at 1550 nm.

9. A waveguide as claimed in claim 1 further comprising an outer optical cladding layer defined about a periphery of said core and positioned between said first cladding region and said core and between said second cladding region and said core.

10. A waveguide as claimed in claim 9 wherein said outer optical cladding layer comprises a substantially non-electrooptic material.

11. A waveguide as claimed in claim 1 wherein said first and second cladding regions comprise a common electrooptic polymer.

12. A waveguide as claimed in claim 1 wherein the refractive index of the first cladding region is equal to the refractive index of the second cladding region.

13. An electrooptic clad waveguide comprising an optical waveguide core defining a primary axis of propagation $z$, a first cladding region offset from said $z$ axis in a first direction along an $x$ axis perpendicular to said $z$ axis, and a second cladding region offset from said $z$ axis in a second direction along said $x$ axis, wherein:

said optical waveguide core comprises a substantially non-electrooptic material defining a refractive index $n_1$;

said first cladding region comprises an electrooptic polymer defining a refractive index that is less than $n_1$;

said second cladding region comprises an electrooptic polymer defining a refractive index that is less than $n_1$; and

said first and second cladding regions are poled in perpendicular directions.

14. A waveguide as claimed in claim 13 further comprising a set of control electrodes arranged to create an electric field in said first and second cladding regions.

15. A waveguide as claimed in claim 13 wherein said set of control electrodes are arranged to create an electric field in said first cladding region that is substantially perpendicular to an electric field created in said second cladding region.

16. A waveguide as claimed in claim 15 wherein said control electrodes are arranged such that a quantitative combination of said electric field and said poling in said first cladding region is substantially equivalent to a quantitative combination of said electric field and said poling in said second cladding region.

17. An electrooptic clad waveguide comprising an optical waveguide core defining a primary axis of propagation $z$, a first cladding region offset from said $z$ axis in a first direction along an $x$ axis perpendicular to said $z$ axis, a second cladding region offset from said $z$ axis in a second direction along said $x$ axis, and first and second control electrodes, wherein:

said optical waveguide core comprises a substantially non-electrooptic material defining a refractive index $n_1$;

said first cladding region comprises an electrooptic polymer defining a refractive index that is less than $n_1$;

said second cladding region comprises an electrooptic polymer defining a refractive index that is less than $n_1$;

said first and second control electrodes are arranged to enable electrooptic modification of said refractive indices of said first and second cladding regions by creating a contoured electric field in said first and second cladding regions;

said contoured electric field and said respective directions of polarization in said first and second cladding regions define a polarization-independent waveguide structure along said primary axis of propagation of said electrooptic clad waveguide; and

said first and second cladding regions are poled along substantially the same contour of said electric field.

18. A waveguide as claimed in claim 17 wherein said contoured electric field is substantially symmetric relative to a plane defined by said $z$ axis and a $y$ axis perpendicular to said $x$ axis and said $z$ axis.

19. A waveguide as claimed in claim 17 wherein said contoured electric field is defined by substantially equivalent $x$ and $y$ components in an $x$-$y$ plane defined by said $x$ and $y$ axes.

20. A waveguide as claimed in claim 17 wherein:

said contoured electric field is defined by $x$ and $y$ components in an $x$-$y$ plane defined by said $x$ and $y$ axes; and

said contoured electric field is established such that said $x$ and $y$ components in each of said cladding regions define substantially equivalent phase control of respective TE and TM modes of propagation of an optical signal propagating along said primary axis of propagation $z$.

21. A waveguide as claimed in claim 17 wherein:

an optical signal having respective TE and TM modes of propagation may pass along said primary axis of propagation $z$; and

said arrangement of said first and second control electrodes and said polarization of said first and second cladding regions enable substantially equivalent phase modification of said TE and TM modes of said optical signal.

22. A waveguide as claimed in claim 17 wherein said first and second control electrodes cooperate with a dielectric constant medium to create said contoured electric field in said first and second cladding regions.

23. A waveguide as claimed in claim 22 wherein said first and second cladding regions are at least partially disposed between said first and second control electrodes and said dielectric constant medium.

24. A waveguide as claimed in claim 22 wherein said first and second control electrodes are disposed on a first surface of said electrooptic clad waveguide and said dielectric constant medium is disposed on a second surface of said electrooptic clad waveguide opposite said first surface.

25. An electrooptic waveguide for an optical signal, said optical signal including both a horizontally oriented component TE and a vertically oriented component TM, said waveguide comprising a plurality of control electrodes, an optical waveguide core, and an electrooptic cladding optically coupled to said optical waveguide core, wherein:

said control electrodes are positioned to generate a contoured electric field across said cladding;

said cladding is poled along a poling contour;

said cladding defines an array of local TM indices of refraction $n_{TM}$ corresponding to the indices of refraction for said vertically oriented component TM of said optical signal in said cladding;

said cladding defines an array of local TE indices of refraction $n_{TE}$ corresponding to the indices of refraction for said horizontally oriented component TE of said optical

signal in said cladding;

said local TM indices $n_{TM}$ and said local TE indices $n_{TE}$ are each a function of a first electrooptic coefficient $r_{PP}$ for light parallel to a local component of said contoured electric field and a second electrooptic coefficient $r_{IP}$ for light perpendicular to a local component of said contoured electric field;

a difference between said first and second electrooptic coefficients $r_{PP}$ and $r_{IP}$ defines an optical birefringence of an electrooptic cladding material defining said cladding;

said local TM indices $n_{TM}$ collectively define a TM mode index of said waveguide;

said local TE indices $n_{TE}$ collectively define a TE mode index of said waveguide; and

said respective orientations of said contoured electric field and said poling contour are configured to compensate for said optical birefringence of said electrooptic cladding material such that said TM mode index of said waveguide is substantially equal to said TE mode index of said waveguide.

26. An electrooptic waveguide as claimed in claim 25 wherein said contoured electric field and said poling contour are asymmetric relative to a primary axis of propagation defined by said waveguide core.

27. An electrooptic waveguide as claimed in claim 25 wherein said contoured electric field and said poling contour lie along a common contour.

28. An electrooptic waveguide as claimed in claim 25 wherein said electrooptic cladding defines at least two cladding regions on opposite sides of said waveguide core and wherein said contoured electric field comprises:

a vertical electric field component within a first one of said pair cladding regions that is larger than a vertical component in a second one of said cladding regions; and

a horizontal electric field component within said first cladding region that is smaller than a horizontal component in said second cladding region.

29. An electrooptic waveguide as claimed in claim 25 wherein:

said waveguide further comprises a controller coupled to said control electrodes;

said controller is programmed to operate said control electrodes at a poling voltage and a driving voltage; and

said poling voltage and said driving voltage are poled such that contra-directional electric fields are created in said cladding by application of said poling voltage and said driving voltage.

30. An electrooptic waveguide as claimed in claim 25 wherein said optical waveguide core comprises a material selected from an electrooptic polymer, silica, and doped silica.

31. An electrooptic waveguide as claimed in claim 25 wherein said electrooptic cladding comprises an electrooptic polymer.

32. An electrooptic waveguide as claimed in claim 25 wherein said electrooptic cladding comprises an anisotropic electrooptic material.

33. An electrooptic waveguide as claimed in claim 25 wherein:

at least two of said control electrodes lie in a common edge plane;

an axis of symmetry of said control electrodes is perpendicular to said common edge plane; and

said core is offset from said axis of symmetry of said control electrodes and from said common edge plane.

34. An electrooptic waveguide as claimed in claim 33 wherein:

a third electrode of said control electrodes lies in a plane offset from said common edge plane; and

said core lies between said common edge plane and said offset plane.

35. An electrooptic waveguide as claimed in claim 25 wherein:

said control electrodes define an asymmetric configuration; and

said waveguide comprises at least two control electrodes lying in parallel planes

and said core is positioned between said parallel planes, unequal distances from said control electrodes.

36. An electrooptic waveguide as claimed in claim 25 wherein:

said control electrodes define an asymmetric configuration;

said waveguide comprises at least two control electrodes lying in parallel planes and said core is positioned between said parallel planes; and

at least one of said control electrodes is limited to extend for a majority of its width along one side of said core in one of said parallel planes.

37. An electrooptic waveguide as claimed in claim 25 wherein:

said control electrodes define an asymmetric configuration;

said waveguide comprises at least two control electrodes lying in parallel planes and said core is positioned between said parallel planes;

one of said control electrodes is limited to extend for a majority of its width along one side of said core in one of said parallel planes; and

another of said control electrodes is limited to extend for a majority of its width along another side of said core in another of said parallel planes.

38. An electrooptic waveguide as claimed in claim 37 wherein said core is positioned unequal distances from said control electrodes.

39. An electrooptic waveguide as claimed in claim 25 wherein:

said control electrodes define an asymmetric configuration;

at least two of said control electrodes lie in a common edge plane and a third control electrode lies in a plane parallel to said common edge plane.

40. An electrooptic waveguide as claimed in claim 39 wherein said core lies between said common edge plane and said parallel plane.

41. An electrooptic waveguide as claimed in claim 25 wherein said control electrodes define a symmetric configuration.

42. An electrooptic waveguide as claimed in claim 25 wherein said control electrodes define an asymmetric configuration.

43. An electrooptic waveguide as claimed in claim 25 wherein:

said control electrodes define an asymmetric configuration; and

said core is positioned unequal distances from at least two of said control electrodes.

44. An electrooptic waveguide as claimed in claim 43 wherein said core is positioned unequal distances from at least three of said control electrodes.

45. An electrooptic waveguide as claimed in claim 25 wherein:

said control electrodes define an asymmetric configuration; and

said control electrodes define substantially equal thicknesses and said core is positioned unequal distances from said control electrodes.

46. An electrooptic waveguide as claimed in claim 25 wherein:

at least two of said control electrodes lie in a common edge plane and a third control electrode lies in a plane parallel to said common edge plane;

said core lies between said common edge plane and said parallel plane; and

said core is positioned unequal distances from said two control electrodes lying in said common edge plane.

47. An electrooptic waveguide as claimed in claim 25 wherein:

at least two of said control electrodes lie in a common edge plane and a third control electrode lies in a plane parallel to said common edge plane;

said core lies between said common edge plane and said parallel plane; and

said third electrode extends to one side of said core for a majority of its width along said parallel plane.

48. An electrooptic waveguide as claimed in claim 25 wherein said control electrodes are spaced from said core by between about 1 μm and about 10 μm.

49. An electrooptic waveguide as claimed in claim 25 wherein said optical waveguide core comprises a substantially non-electrooptic material.

50. An electrooptic waveguide for an optical signal, said optical signal including a horizontally oriented component TE and a vertically oriented component TM, said waveguide comprising a plurality of control electrodes, an optical waveguide core defining a primary axis of propagation, and an electrooptic cladding at least partially surrounding said core, wherein:

said control electrodes are positioned to generate a contoured electric field across said cladding;

said cladding is poled along a poling contour; and

at least one of said contoured electric field and said poling contour are asymmetric relative to a plane intersecting said waveguide core and extending along said primary axis of propagation.

51. An electrooptic waveguide as claimed in claim 50 wherein said contoured electric field and said poling contour are asymmetric relative to said plane intersecting said waveguide core.

52. An electrooptic waveguide as claimed in claim 51 wherein said electric field and said poling lines follow a common contour.

53. An electrooptic waveguide as claimed in claim 50 wherein said contoured electric field is asymmetric relative to said plane intersecting said waveguide core.

54. An electrooptic waveguide as claimed in claim 50 wherein said poling contour is asymmetric relative to said plane intersecting said waveguide core.

55. An electrooptic waveguide as claimed in claim 50 wherein said intersecting plane is normal to a surface of said waveguide core.

56. An electrooptic waveguide as claimed in claim 50 wherein respective orientations of said contoured electric field and said poling contour are configured to compensate for an optical birefringence of an electrooptic cladding material defining said cladding such that a TM mode index corresponding to the indices of refraction for a vertically oriented component TM of said optical signal in said cladding is substantially equal to a TE mode index corresponding to the indices of refraction for a horizontally oriented component TE of said optical signal in said cladding.

57. An electrooptic waveguide as claimed in claim 50 wherein said electrooptic cladding defines at least two cladding regions on opposite sides of said waveguide core and wherein said contoured electric field comprises:

a vertical electric field component within a first one of said pair cladding regions that is larger than a vertical component in a second one of said cladding regions; and

a horizontal electric field component within said first cladding region that is smaller than a horizontal component in said second cladding region.

58. An electrooptic waveguide for an optical signal, said optical signal including a horizontally oriented component TE and a vertically oriented component TM, said waveguide comprising a plurality of control electrodes, an electrooptic optical waveguide core defining a primary axis of propagation, and a cladding at least partially surrounding said core, wherein:

said control electrodes are positioned to generate a contoured electric field across said core;

said core is poled along a poling contour; and

at least one of said contoured electric field and said poling contour are asymmetric relative to a plane intersecting said waveguide core and extending along said primary axis of propagation.

59. An electrooptic waveguide as claimed in claim 58 wherein said cladding comprises a substantially non-electrooptic material.

60. An electrooptic waveguide as claimed in claim 59 wherein said cladding comprises an electrooptic material.

61. An integrated optical device comprising an optical input, an optical output, an electrooptic clad waveguide, and first and second control electrodes, wherein:

said electrooptic clad waveguide is arranged along an optical path defined between said optical input and said optical output;

said electrooptic clad waveguide is characterized by an optical phase delay $\Phi=2\pi L n_{eff}/\lambda$, where $n_{eff}$ is the effective index of refraction of said waveguide, $L$ is the length over which the phase delay occurs, and $\lambda$ is the wavelength of light propagating along said optical path;

said electrooptic clad waveguide comprises an optical waveguide core defining a primary axis of propagation $z$, a first cladding region offset from said $z$ axis in a first direction along an $x$ axis perpendicular to said $z$ axis, and a second cladding region offset from said $z$ axis in a second direction along said $x$ axis;

said optical waveguide core comprises a substantially non-electrooptic material defining a refractive index $n_1$;

said first cladding region comprises an electrooptic polymer defining a refractive index that is less than $n_1$;

said second cladding region comprises an electrooptic polymer defining a refractive index that is less than $n_1$;

said waveguide core defines a cross-sectional $x$ axis width that decreases from a region outside of said first and second cladding regions to a region bounded by said first and second cladding regions; and

said first and second control electrodes are arranged to create an electric field in said first and second cladding regions capable of changing said refractive indices of said first and second electrooptic cladding regions without a corresponding change in said refractive index $n_1$ of said waveguide core so as to induce a core-independent change in $n_{eff}$ and a corresponding change in said optical phase delay $\Phi$ of said waveguide.

62. An integrated optical device as claimed in claim 61 wherein said cross-sectional $x$-axis decreases in width by about 60 %.

63. An integrated optical device as claimed in claim 61 wherein said cross-sectional $x$-axis decreases in width by at least about 40%.

64. An integrated optical device as claimed in claim 61 wherein said cross-sectional $x$ axis decreases in width to about 3μm in said region bounded by said first and second cladding regions.

65. An integrated optical device as claimed in claim 61 wherein said cross-sectional $x$ axis decreases in width from about 8μm in said region outside of said first and second cladding regions to about 3μm in said region bounded by said first and second cladding regions.

66. An integrated optical device as claimed in claim 61 wherein said cross-sectional $x$ axis decreases in width from about 5μm in said region outside of said first and second cladding regions to about 3μm in said region bounded by said first and second cladding regions.

67. An integrated optical device as claimed in claim 61 wherein said first and second cladding regions are poled in opposite directions.

68. An integrated optical device as claimed in claim 61 wherein said first and second cladding regions are poled in perpendicular directions.

69. An integrated optical device as claimed in claim 61 wherein said first and second cladding regions are poled in substantially the same direction.

70. An integrated optical device as claimed in claim 61 wherein said optical waveguide core comprises a silica waveguide and said refractive index $n_1$ is about 1.45 at 1550 nm.

71. An integrated optical device comprising first and second waveguides arranged to define a Mach-Zehnder interferometer including first and second directional coupling regions, an intermediate coupling region disposed between said first and second directional coupling regions, a set of control electrodes, an optical input, and at least one optical output, wherein:

at least one of said first and second waveguides comprises an electrooptic clad waveguide comprising a substantially non-electrooptic optical waveguide core defining a refractive index $n_1$;

said waveguide core of said electrooptic clad waveguide is disposed between first and second cladding regions in said intermediate coupling region;

said first cladding region comprises a poled electrooptic polymer defining a refractive index that is less than $n_1$;

said second cladding region comprises a poled electrooptic polymer defining a refractive index that is less than $n_1$;

said control electrodes are arranged to create an electric field in said first and second cladding regions capable of changing said refractive indices of said first and second electrooptic cladding regions so as to induce a change in an effective index of refraction $n_{eff}$ of said electrooptic clad waveguide; and

said control electrodes are arranged such that a quantitative combination of said electric field and said poling in said first cladding region is substantially equivalent to a quantitative combination of said electric field and said poling in said second cladding region, whereby an output intensity $I_{out}$ at one of said optical outputs is related to an input intensity $I_{in}$ according to one of the following equations

$$|I_{out}|^2 = |I_{in}|^2 \sin^2\left(\frac{\phi}{2}\right)$$

$$|I_{out}|^2 = |I_{in}|^2 \cos^2\left(\frac{\phi}{2}\right)$$

where $\Phi$ represents optical phase delay resulting from said change in said effective index of refraction $n_{eff}$ of said electrooptic clad waveguide.

72. An integrated optical device as claimed in claim 71 wherein said first and second cladding regions are poled in opposite directions.

73. An integrated optical device as claimed in claim 71 wherein said first and second cladding regions are poled in perpendicular directions.

74. An integrated optical device as claimed in claim 71 wherein said first and second cladding regions are poled in substantially the same direction.

75. An integrated optical device as claimed in claim 71 wherein said waveguide core defines a cross-sectional $x$ axis width that decreases from a region outside of said first and second cladding regions to a region bounded by said first and second cladding regions.

76. An integrated optical device as claimed in claim 71 wherein said optical waveguide core comprises a silica waveguide and said refractive index $n_1$ is about 1.45 at 1550 nm.

77. An integrated optical device comprising first and second electrooptic clad waveguides arranged to define a Mach-Zehnder interferometer including first and second directional coupling regions, an intermediate coupling region disposed between said first and second directional coupling regions, a set of control electrodes, first and second optical inputs, and first and second optical outputs, wherein:

said first electrooptic clad waveguide comprises a substantially non-electrooptic optical waveguide core defining a refractive index $n_1$;

said waveguide core of said first waveguide is disposed between first and second cladding regions of said first waveguide in said intermediate coupling region;

said first cladding region of said first waveguide comprises a poled electrooptic polymer defining a refractive index that is less than $n_1$;

said second cladding region of said first waveguide comprises a poled electrooptic polymer defining a refractive index that is less than $n_1$;

said second electrooptic clad waveguide comprises a substantially non-electrooptic optical waveguide core defining a refractive index $n_1$;

said waveguide core of said second waveguide is disposed between first and second cladding regions of said second waveguide in said intermediate coupling region;

said first cladding region of said second waveguide comprises a poled electrooptic polymer defining a refractive index that is less than $n_1$;

said second cladding region of said second waveguide comprises a poled electrooptic polymer defining a refractive index that is less than $n_1$;

said poling of said first and second cladding regions of said first waveguide is substantially perpendicular to said poling of said first and second cladding regions of said second waveguide; and

said control electrodes are arranged to create an electric field in said first and second cladding regions of said first and second waveguides to induce a change in an effective index of refraction $n_{eff}$ of said first and second waveguides, whereby input optical signals may be directed selectively to separate ones of said optical outputs by controlling said electric field.

78. An integrated optical device as claimed in claim 77 wherein said poling of said first and second cladding regions of said first and second waveguides and said arrangement of said control electrodes are such that, upon creation of said electric field, TE and TM polarized light propagating along said first and second waveguides are phase modulated to different degrees in each of said waveguides and to substantially equal degrees across both of said waveguides.

79. An integrated optical device as claimed in claim 77 wherein said waveguide core defines a cross-sectional $x$ axis width that decreases from a region outside of said first and second cladding regions to a region bounded by said first and second cladding regions.

80. An integrated optical device as claimed in claim 77 wherein said optical waveguide core comprises a silica waveguide and said refractive index $n_1$ is about 1.45 at 1550 nm.

81. An integrated optical device comprising first and second waveguides arranged to define a Mach-Zehnder interferometer including first and second directional coupling regions, an intermediate coupling region disposed between said first and second

directional coupling regions, a set of control electrodes, an optical input, and at least one optical output, wherein:

at least one of said first and second waveguides comprises an electrooptic clad waveguide comprising a substantially non-electrooptic optical waveguide core defining a refractive index $n_1$;

said waveguide core of said electrooptic clad waveguide is disposed between first and second cladding regions in said intermediate coupling region;

said first cladding region comprises a poled electrooptic polymer defining a refractive index that is less than $n_1$;

said second cladding region comprises a poled electrooptic polymer defining a refractive index that is less than $n_1$;

said control electrodes form a traveling wave stripline and are arranged to create an electric field in said first and second cladding regions capable of changing said refractive indices of said first and second electrooptic cladding regions so as to induce a change in an effective index of refraction $n_{eff}$ of said electrooptic clad waveguide;

said traveling wave stripline is characterized by a dielectric constant ε selected such that an optical signal propagating in said electrooptic clad waveguide propagates at the same velocity as an electrical signal propagating in said traveling wave stripline; and

said control electrodes are arranged such that a quantitative combination of said electric field and said poling in said first cladding region is substantially equivalent to a quantitative combination of said electric field and said poling in said second cladding region, whereby an output intensity $I_{out}$ at one of said optical outputs is related to an input intensity $I_{in}$ according to one of the following equations

$$|I_{out}|^2 = |I_{in}|^2 \sin^2\left(\frac{\phi}{2}\right)$$

$$|I_{out}|^2 = |I_{in}|^2 \cos^2\left(\frac{\phi}{2}\right)$$

where $\Phi$ represents optical phase delay resulting from said change in said effective index of refraction $n_{eff}$ of said electrooptic clad waveguide.

82. An integrated optical device as claimed in claim 81 wherein said integrated optical device is configured such that $\varepsilon = \left(n_{eff}\right)^2$, where ε is the dielectric constant of said traveling wave stripline at microwave frequencies and $n_{eff}$ is the effective index of refraction of said electrooptic clad waveguide.

83. An integrated optical device as claimed in claim 81 wherein said traveling wave stripline includes a microwave input port and a 50Ω termination.

84. An integrated optical device as claimed in claim 81 wherein said waveguide core defines a cross-sectional $x$ axis width that decreases from a region outside of said first and second cladding regions to a region bounded by said first and second cladding regions.

85. An integrated optical device as claimed in claim 81 wherein said optical waveguide core comprises a silica waveguide and said refractive index $n_1$ is about 1.45 at 1550 nm.

86. An integrated optical device comprising first and second electrooptic clad waveguides of unequal length arranged to define an asymmetric Mach-Zehnder interferometer including first and second directional coupling regions, an intermediate coupling region disposed between said first and second directional coupling regions, a set of control electrodes, an optical input, and first and second optical outputs, wherein:

said first electrooptic clad waveguide comprises a substantially non-electrooptic optical waveguide core defining a refractive index $n_1$;

said waveguide core of said first waveguide is disposed between first and second cladding regions of said first waveguide in said intermediate coupling region;

said first cladding region of said first waveguide comprises a poled electrooptic polymer defining a refractive index that is less than $n_1$;

said second cladding region of said first waveguide comprises a poled electrooptic polymer defining a refractive index that is less than $n_1$;

said second electrooptic clad waveguide comprises a substantially non-electrooptic optical waveguide core defining a refractive index $n_1$;

said waveguide core of said second waveguide is disposed between first and second cladding regions of said second waveguide in said intermediate coupling region;

said first cladding region of said second waveguide comprises a poled electrooptic polymer defining a refractive index that is less than $n_1$;

said second cladding region of said second waveguide comprises a poled electrooptic polymer defining a refractive index that is less than $n_1$;

said poling of said first and second cladding regions of said first waveguide is substantially perpendicular to said poling of said first and second cladding regions of said second waveguide; and

said control electrodes are arranged to create an electric field in said first and second cladding regions of said first and second waveguides to induce a change in an effective index of refraction $n_{eff}$ of said first and second waveguides, whereby first and second wavelength components of an input optical signal may be directed selectively to separate ones of said optical outputs by controlling said electric field.

87. An integrated optical device as claimed in claim 86 wherein said poling of said first and second cladding regions of said first and second waveguides and said arrangement of said control electrodes are such that, upon creation of said electric field, TE and TM polarized light propagating along said first and second waveguides are phase modulated to different degrees in each of said waveguides and to substantially equal degrees across both of said waveguides.

88. An integrated optical device as claimed in claim 86 wherein said waveguide core defines a cross-sectional $x$ axis width that decreases from a region outside of said first and second cladding regions to a region bounded by said first and second cladding regions.

89. An integrated optical device as claimed in claim 86 wherein said optical waveguide core comprises a silica waveguide and said refractive index $n_1$ is about 1.45 at 1550 nm.

90. An integrated optical device comprising first and second electrooptic clad waveguides arranged to define a directional coupling region, a set of control electrodes, first and second optical inputs, and first and second optical outputs, wherein:

said first electrooptic clad waveguide comprises a substantially non-electrooptic optical waveguide core defining a refractive index $n_1$;

said waveguide core of said first waveguide is disposed between a first outer electrooptic cladding region and an electrooptic gap region in said directional coupling region;

said first outer cladding region comprises a poled electrooptic polymer defining a refractive index that is less than $n_1$;

said electrooptic gap region comprises a poled electrooptic polymer defining a refractive index that is less than $n_1$;

said second electrooptic clad waveguide comprises a substantially non-electrooptic optical waveguide core defining a refractive index $n_1$;

said waveguide core of said second waveguide is disposed between a second outer electrooptic cladding region and said electrooptic gap region in said directional coupling region;

said second outer cladding region comprises a poled electrooptic polymer defining a refractive index that is less than $n_1$;

said control electrodes are arranged to create an electric field across said outer cladding regions and said electrooptic gap region, whereby an optical signal incident in one of said waveguides may be switched to the other of said waveguides.

91. An integrated optical device as claimed in claim 90 wherein said outer cladding regions and said electrooptic gap region are poled to render said directional coupling region polarization-independent.

92. An integrated optical device as claimed in claim 90 wherein said outer cladding regions are poled perpendicular to said electrooptic gap region.

93. An integrated optical device as claimed in claim 92 wherein:

said control electrodes are arranged to enable electrooptic modification of said refractive indices of said first and second cladding regions by creating a contoured electric field in said outer cladding regions and said electrooptic gap region;

said contoured electric field and said respective directions of polarization in said outer cladding regions and said electrooptic gap region define a polarization-independent waveguide structure along a primary axis of propagation of said first and second electrooptic clad waveguides; and

said first and second cladding regions are poled along substantially the same contour of said electric field.

94. An integrated optical device as claimed in claim 93 wherein said contoured electric field is substantially symmetric relative to said electrooptic gap region.

95. An integrated optical device as claimed in claim 93 wherein said control electrodes cooperate with a dielectric constant medium to create said contoured electric field.

96. An integrated optical device as claimed in claim 93 wherein said first and second cladding regions are at least partially disposed between said control electrodes and said dielectric constant medium.

97. An optical waveguide comprising an optical input, an optical output, and a waveguide core, wherein:

said waveguide core defines a core height dimension $h$ that remains substantially constant between said optical input and said optical output;

said core width dimension defines an input width $w_1$ at said optical input, an output width $w_2$ at said optical output, an increased-width $w_0$ along a phase compensating element of said waveguide core, and a decreased-width $w_3$ along a thinned-down portion of said waveguide core;

said increased-width $w_0$ is greater than said input width; and

said decreased-width $w_3$ is less than said input width.

98. An integrated optical device as claimed in claim 97 wherein said input width $w_1$ and said output width $w_2$ are substantially equal to said core height dimension $h$.

99. An integrated optical device as claimed in claim 97 wherein:

said thinned-down portion introduces a first phase shift in an optical signal propagating from said optical input to said optical output; and

said phase compensating element introduces a second phase shift in said optical signal; and

said first phase shift is substantially equal and opposite in magnitude to said second phase shift.

100. An integrated optical device as claimed in claim 97 wherein said input width $w_1$ and said output width $w_2$ are about 5μm, said increased-width $w_0$ is about 10μm, and said decreased-width $w_3$ is about 3μm.

101. An integrated optical device as claimed in claim 97 wherein said phase compensating element and said thinned-down portion of said waveguide are coupled to adjacent waveguide portions via tapered transitions.

102. An integrated optical device as claimed in claim 101 wherein said thinned-down portion defines a length of about 2 cm, said compensating element defines a length of at least about 2cm, and said tapered transitions define a length of about 0.3 cm.

103. An integrated optical device as claimed in claim 97 wherein said thinned-down portion defines a length of about 2 cm, said compensating element defines a length of at least about 2cm.

104. An optical waveguide comprising an optical input, an optical output, and a waveguide core, wherein:

said waveguide core defines a core height dimension $h$ that remains substantially constant between said optical input and said optical output;

said core width dimension defines an increased-width $w_0$ along a phase compensating element of said waveguide core, and a decreased-width $w_3$ along a thinned-down portion of said waveguide core;

said decreased-width $w_3$ is less than said core height dimension $h$; and

said increased-width $w_0$ is greater than said core height dimension $h$.

105. An integrated optical device comprising an optical input, an optical output, and an optically functional clad waveguide, wherein:

said optically functional clad waveguide is arranged along an optical path defined between said optical input and said optical output;

said optically functional clad waveguide is characterized by an optical phase delay $\Phi=2\pi L n_{eff}/\lambda$, where $n_{eff}$ is the effective index of refraction of said waveguide, $L$ is the length over which the phase delay occurs, and $\lambda$ is the wavelength of light propagating along said optical path;

said optically functional clad waveguide comprises an optical waveguide core defining a primary axis of propagation $z$, a first cladding region offset from said $z$ axis in a first direction along an $x$ axis perpendicular to said $z$ axis, and a second cladding region offset from said $z$ axis in a second direction along said $x$ axis;

said optical waveguide core comprises an optically non-functional material defining a refractive index $n_1$;

said first cladding region defines a refractive index that is less than $n_1$;

said second cladding region defines a refractive index that is less than $n_1$;

said waveguide core defines a cross-sectional $x$ axis width that decreases from a region outside of said first and second cladding regions to a region bounded by said first and second cladding regions; and

said refractive indices of said first and second cladding regions are arranged to change in response to a control parameter without a corresponding change in said refractive index $n_1$ of said waveguide core so as to induce a core-independent change in $n_{eff}$ and a corresponding change in said optical phase delay $\Phi$ of said waveguide.

106. An integrated optical device comprising first and second waveguides arranged to define a Mach-Zehnder interferometer including first and second directional coupling regions, an intermediate coupling region disposed between said first and second directional coupling regions, a set of control electrodes, an optical input, and at least one optical output, wherein:

at least one of said first and second waveguides comprises an optically functional electrooptic clad waveguide comprising an optically non-functional optical waveguide core defining a refractive index $n_1$;

said waveguide core of said clad waveguide is disposed between first and second cladding regions in said intermediate coupling region;

said first cladding region comprises a poled material defining a refractive index that is less than $n_1$;

said second cladding region comprises a poled material defining a refractive index that is less than $n_1$;

said control electrodes are arranged to create an electric field in said first and second cladding regions capable of changing said refractive indices of said first and second cladding regions so as to induce a change in an effective index of refraction $n_{eff}$ of said waveguide; and

said control electrodes are arranged such that a quantitative combination of said electric field and said poling in said first cladding region is substantially equivalent to a quantitative combination of said electric field and said poling in said second cladding region, whereby an output intensity $I_{out}$ at one of said optical outputs is related to an input intensity $I_{in}$ according to one of the following equations

$$|I_{out}|^2 = |I_{in}|^2 \sin^2\left(\frac{\phi}{2}\right)$$

$$|I_{out}|^2 = |I_{in}|^2 \cos^2\left(\frac{\phi}{2}\right)$$

where $\Phi$ represents optical phase delay resulting from said change in said effective index of refraction $n_{eff}$ of said waveguide.

107. An electrooptic clad waveguide comprising an optical waveguide core defining a primary axis of propagation $z$, a first cladding region offset from said $z$ axis in a first direction along an $x$ axis perpendicular to said $z$ axis, and a second cladding region offset from said $z$ axis in a second direction along said $x$ axis, wherein:

said optical waveguide core comprises an optically non-functional material defining a refractive index $n_1$;

said first cladding region comprises an optically functional material defining a refractive index that is less than $n_1$;

said second cladding region comprises an optically functional material defining a refractive index that is less than $n_1$; and

said first and second cladding regions are poled in different directions.

108. An integrated optical device comprising a plurality of channel waveguides and a thermo/electric poling arrangement, wherein:

at least a pair of said waveguides are at least partially bounded along a portion of their length by respective electrooptic cladding regions defining respective polar axes;

said thermo/electric poling arrangement is provided proximate said respective electrooptic cladding regions and is arranged to orient independently said respective polar axes of said cladding regions.

109. An integrated optical device as claimed in claim 108 wherein selected waveguides are connected via respective waveguide branches.

110. An integrated optical device as claimed in claim 108 wherein selected waveguides are connected via respective evanescent coupling regions.

111. An integrated optical device as claimed in claim 108 wherein said channel waveguides comprise an optically non-functional waveguide core.

112. An integrated optical device as claimed in claim 108 wherein:

said thermo/electric poling arrangement is characterized by a selected processing temperature; and

said channel waveguides comprise a ferroelectric material having a Curie temperature greater than said processing temperature of said thermo/electric poling arrangement.

113. An integrated optical device comprising a plurality of channel waveguides and a thermo/electric poling arrangement, wherein:

at least a pair of said waveguides is at least partially bounded along a portion of their length by respective optically functional cladding regions defining respective polar axes;

said thermo/electric poling arrangement is provided proximate said respective optically functional cladding regions and is arranged to orient independently said respective polar axes of said cladding regions.

114. An integrated optical device comprising an optical input, an optical output, and an electrooptic waveguide for an optical signal, said optical signal including a horizontally oriented component TE and a vertically oriented component TM, said waveguide comprising a plurality of control electrodes, an optical waveguide core, and an electrooptic cladding optically coupled to said optical waveguide core, wherein:

said control electrodes are positioned to generate a contoured electric field across said cladding;

said cladding is poled along a poling contour;

said cladding defines an array of local TM indices of refraction $n_{TM}$ corresponding to the indices of refraction for said vertically oriented component TM of said optical signal in said cladding;

said cladding defines an array of local TE indices of refraction $n_{TE}$ corresponding to the indices of refraction for said horizontally oriented component TE of said optical signal in said cladding;

said local TM indices $n_{TM}$ and said local TE indices $n_{TE}$ are each a function of a first electrooptic coefficient $r_{PP}$ for light parallel to a local component of said contoured electric field and a second electrooptic coefficient $r_{IP}$ for light perpendicular to a local component of said contoured electric field;

a difference between said first and second electrooptic coefficients $r_{PP}$ and $r_{IP}$

defines an optical birefringence of an electrooptic cladding material defining said cladding;

said local TM indices $n_{TM}$ collectively define a TM mode index of said waveguide;

said local TE indices $n_{TE}$ collectively define a TE mode index of said waveguide; and

said respective orientations of said contoured electric field and said poling contour are configured to compensate for said optical birefringence of said electrooptic cladding material such that said TM mode index of said waveguide is substantially equal to said TE mode index of said waveguide.

115. An integrated optical device comprising an optical input, an optical output, and an electrooptic waveguide for an optical signal, said optical signal including a horizontally oriented component TE and a vertically oriented component TM, said waveguide comprising a plurality of control electrodes, an optical waveguide core defining a primary axis of propagation, and an electrooptic cladding at least partially surrounding said core, wherein:

said control electrodes are positioned to generate a contoured electric field across said cladding;

said cladding is poled along a poling contour; and

at least one of said contoured electric field and said poling contour are asymmetric relative to a plane intersecting said waveguide core and extending along said primary axis of propagation.

116. A process wherein an electrooptic waveguide is formed by:

providing a waveguide substrate;

positioning an optical waveguide core over a first surface of said substrate;

providing a waveguide superstrate;

forming at least two control electrodes on a first surface of said superstrate, wherein said control electrodes define selected electrode thicknesses;

positioning a viscous electrooptic cladding material over one or both of said first surface of said substrate and said first surface of said superstrate; and

urging said first surface of said waveguide substrate and said first surface of said waveguide superstrate toward each other to create a layer of cladding material between said surfaces, wherein

said cladding material defines a cladding material viscosity selected to permit dispersion of said cladding material about said control electrodes and said core as said first surface of said waveguide substrate and said first surface of said waveguide superstrate are urged toward each other, and

said cladding material is provided in a quantity sufficient to ensure that said layer of cladding material defines a cladding layer thickness at least as large as said selected electrode thicknesses.

117. A process as claimed in claim 116 wherein said control electrodes are formed on a first surface of said superstrate by forming successive electrode plates to said selected electrode thicknesses.

118. A process as claimed in claim 116 wherein said control electrodes are formed to define respectively different electrode thicknesses.

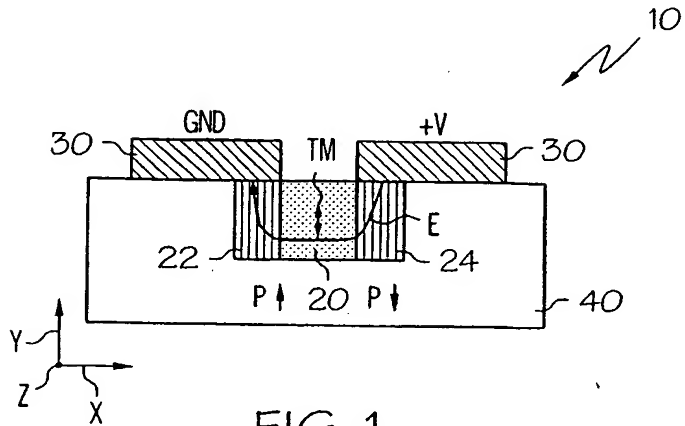



FIG. 1

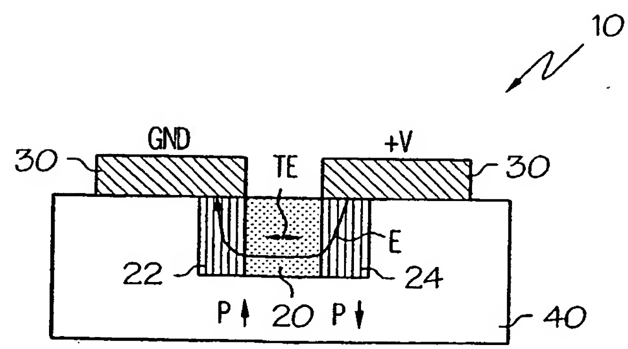
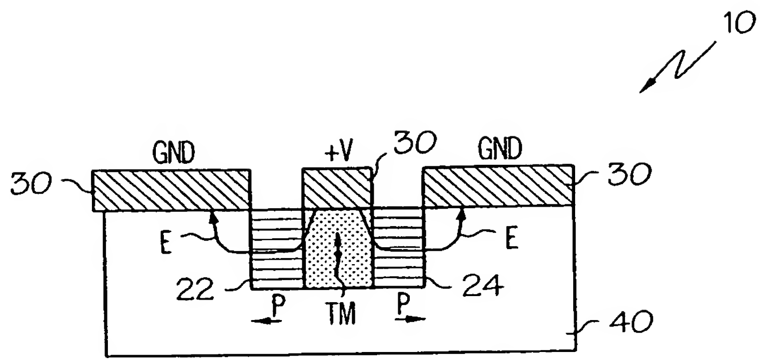



FIG. 2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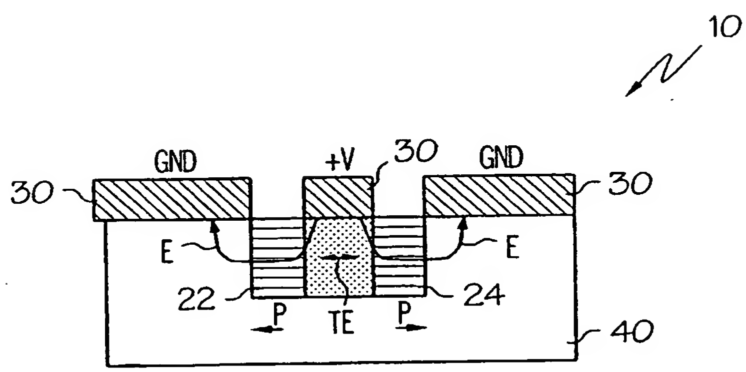
P
TM
P
40

FIG. 3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TE
P
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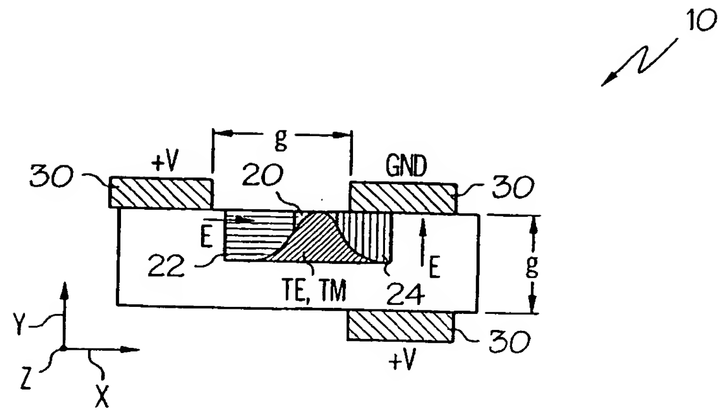
FIG. 4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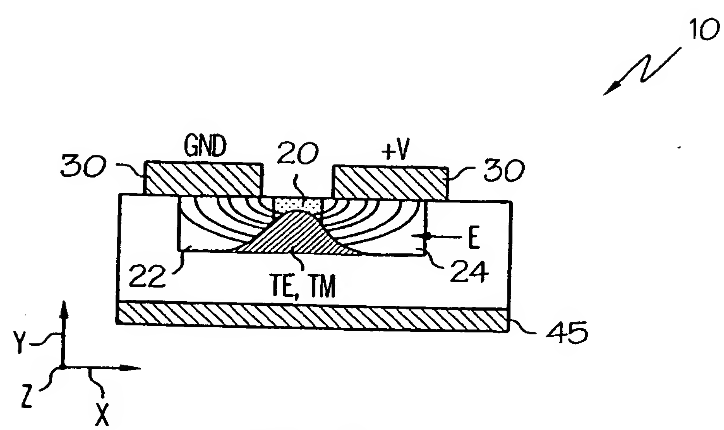
+V
Z
X

FIG. 5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TE, TM
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Y
Z
X

FIG. 6

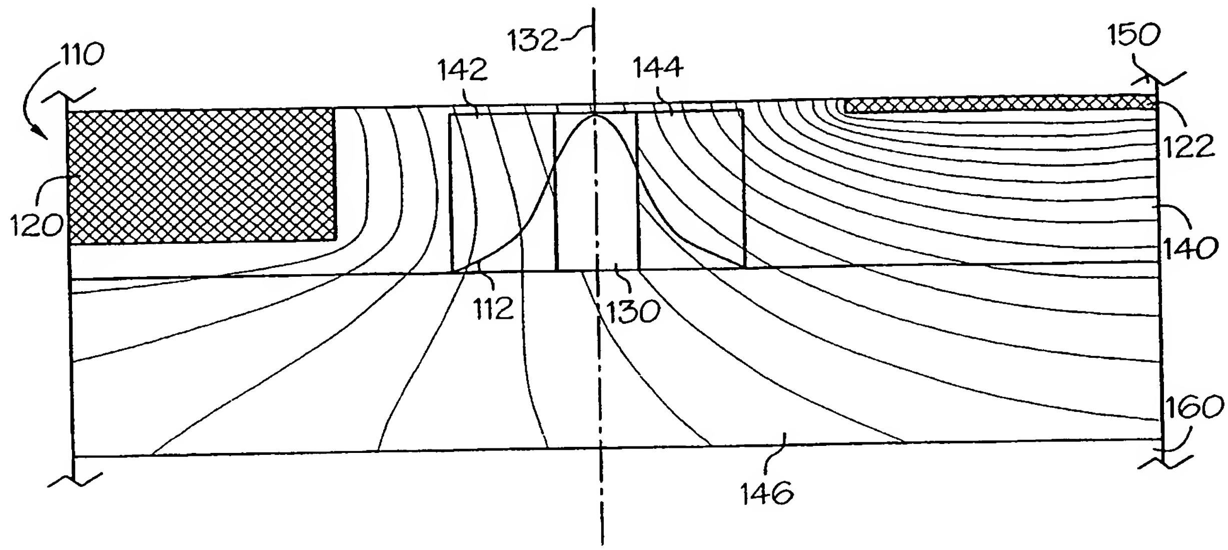
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FIG. 7

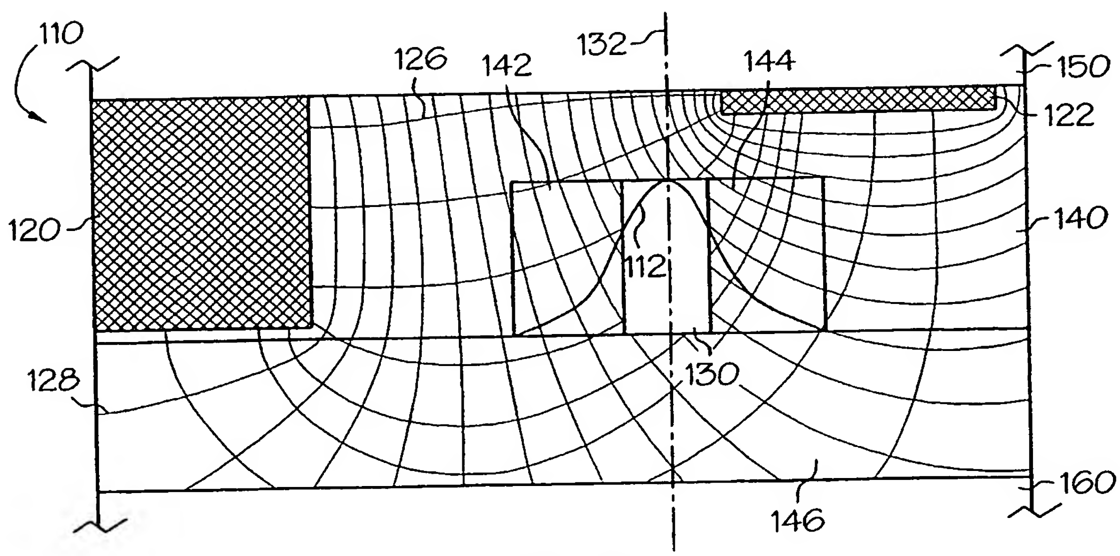
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FIG. 8

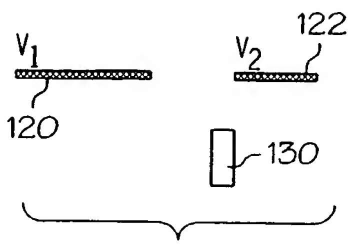


FIG. 9

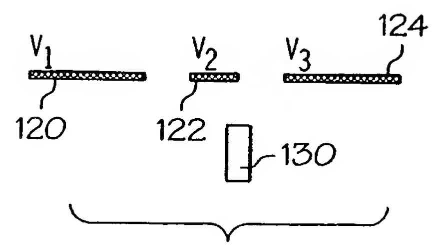


FIG. 10

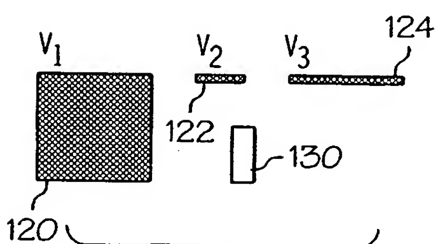


FIG. 11

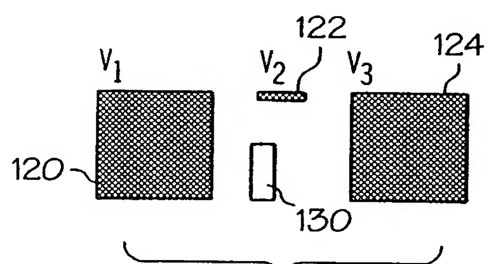


FIG. 12

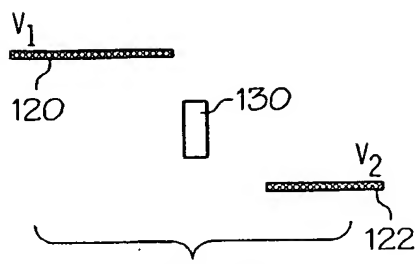


FIG. 13

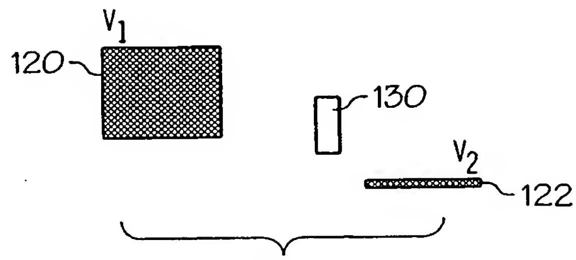


FIG. 14

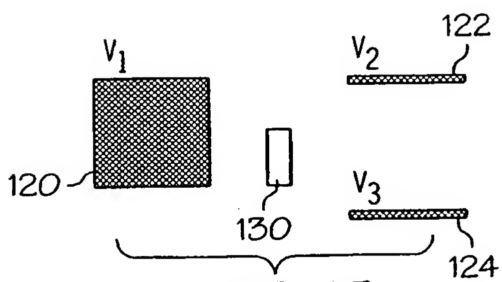


FIG. 15

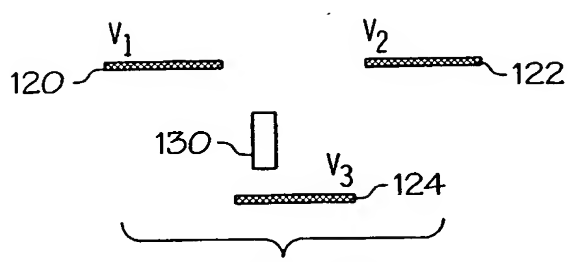


FIG. 16

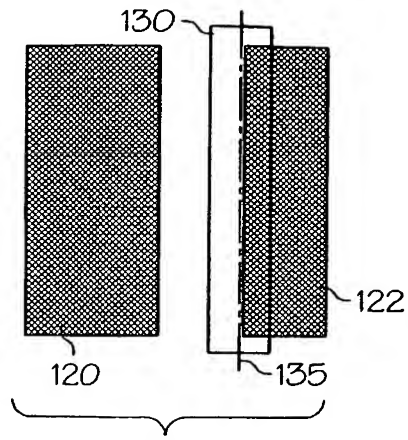


FIG. 17

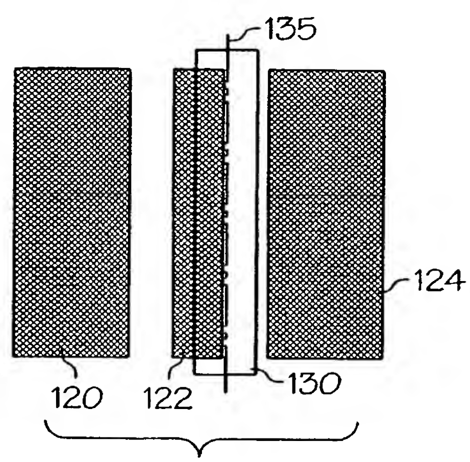


FIG. 18

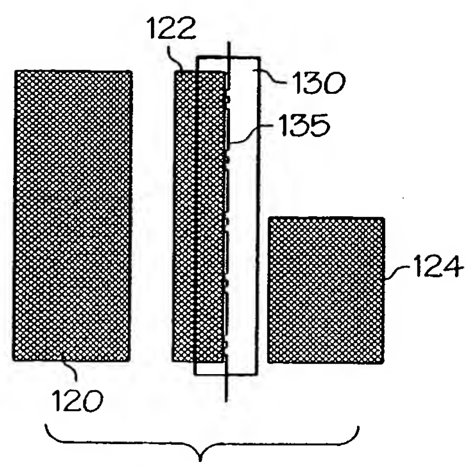


FIG. 19

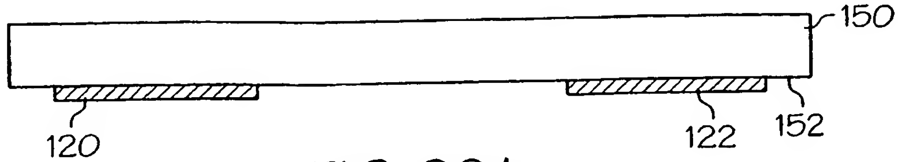

FIG. 20A

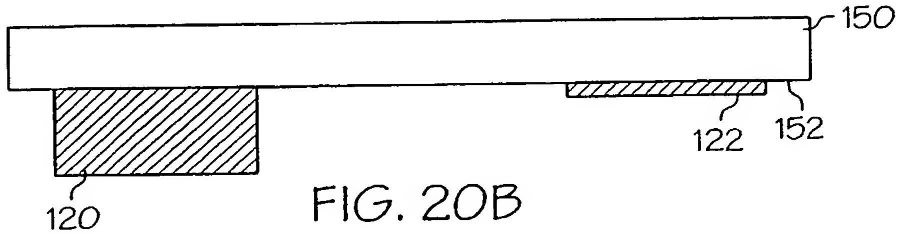

FIG. 20B

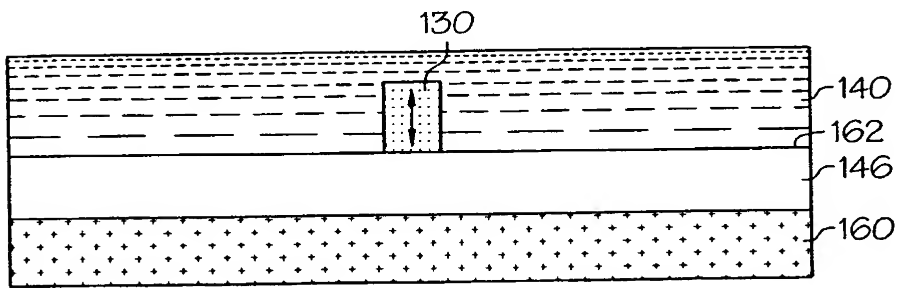

FIG. 20C

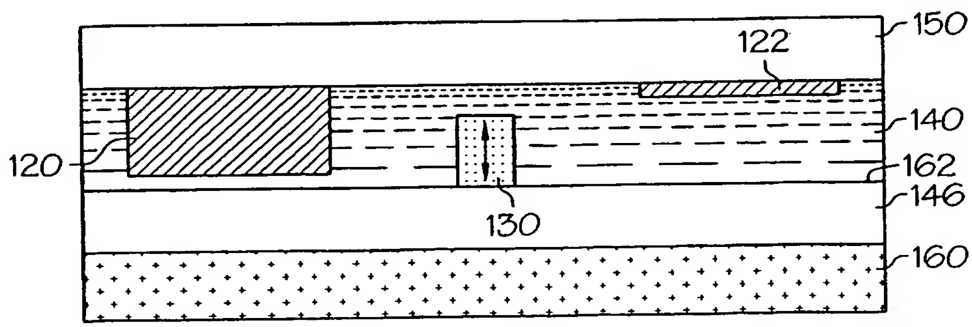

FIG. 20D

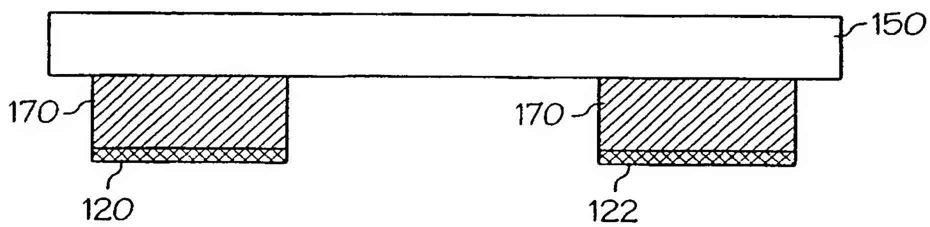


FIG. 21

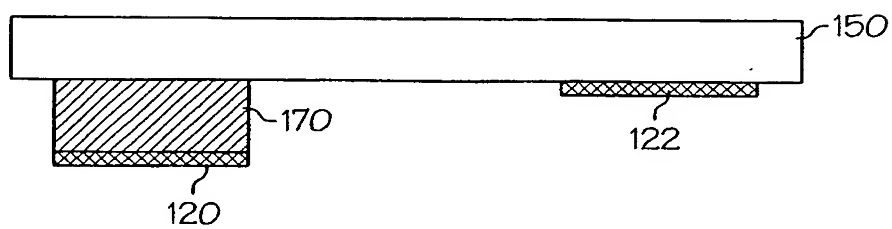


FIG. 22

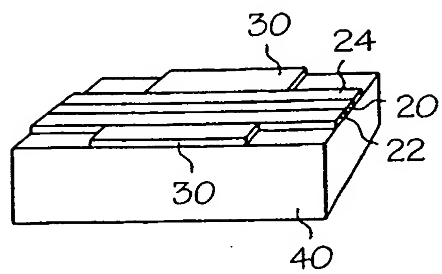


FIG. 23

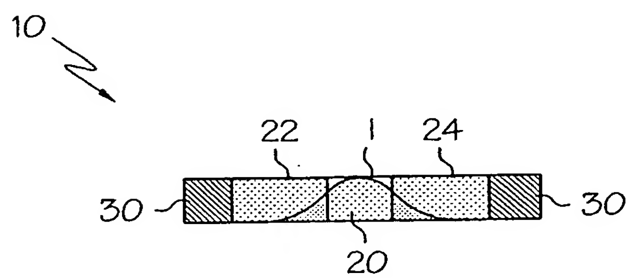


FIG. 24

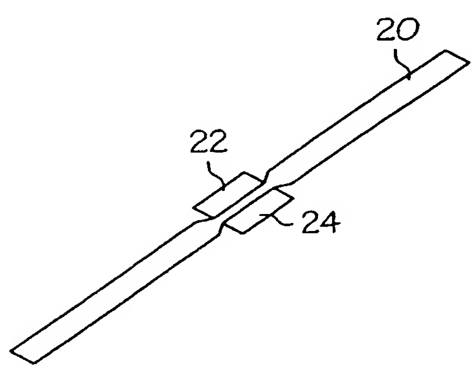


FIG. 25

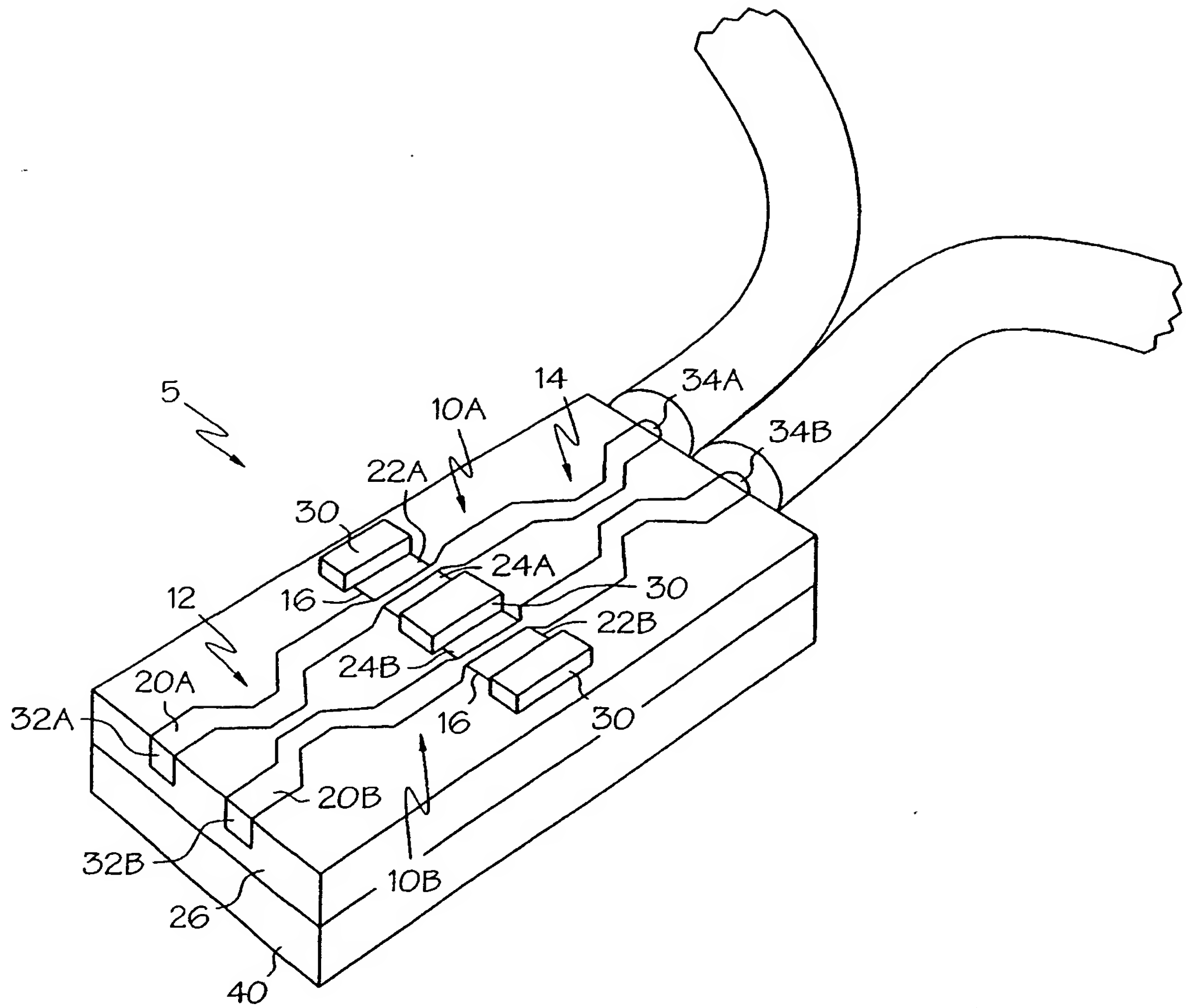
5
14
10A
34A
34B
22A
30
24A
30
16
12
22B
24B
20A
32A
16
30
20B
32B
10B
26
40

FIG. 26

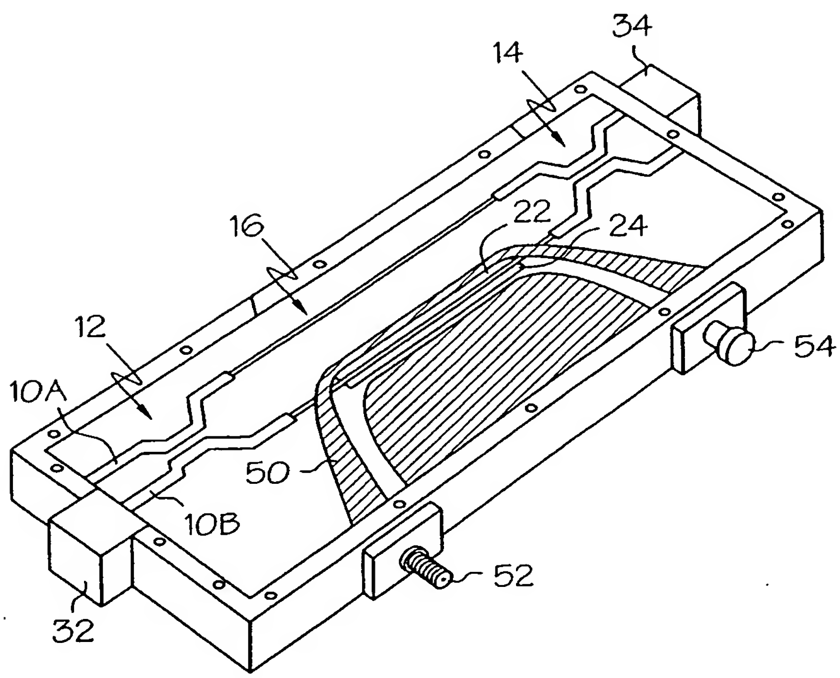


FIG. 27

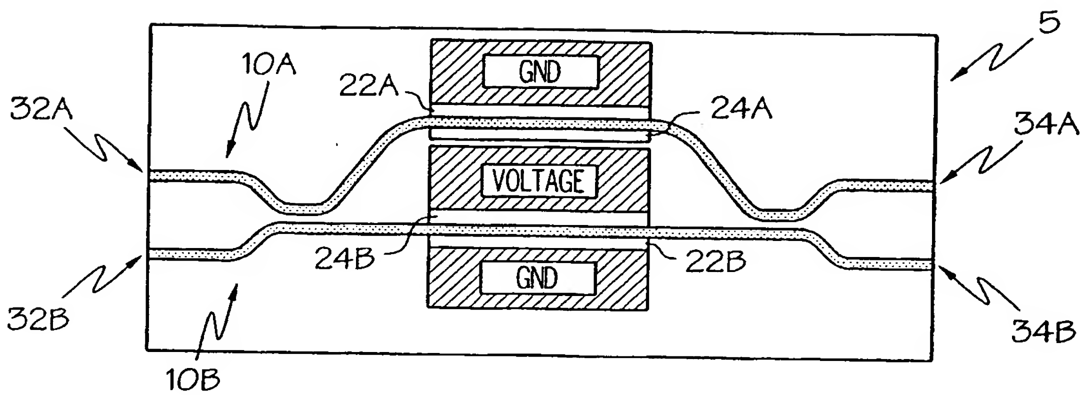
5
10A
22A
GND
24A
32A
34A
VOLTAGE
24B
22B
GND
32B
34B
10B

FIG. 28

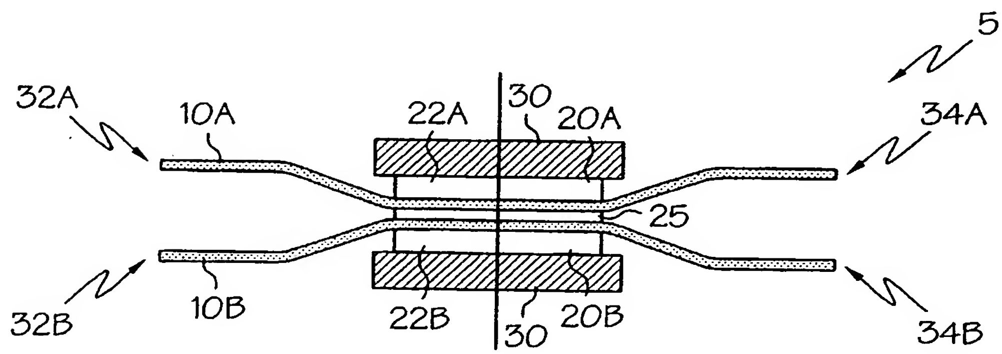
5
32A
10A
22A
30
20A
34A
25
32B
10B
22B
30
20B
34B

FIG. 29

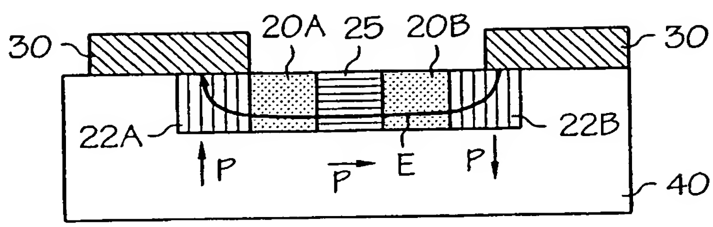


FIG. 30A

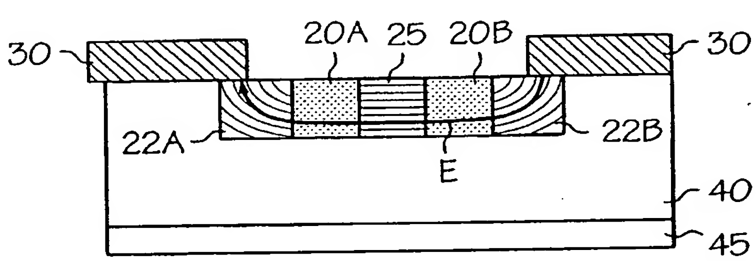


FIG. 30B

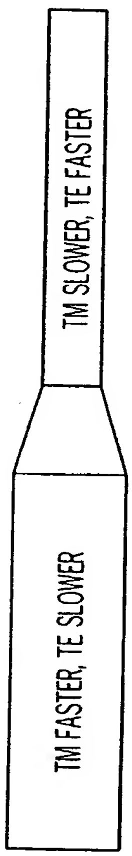
TM FASTER, TE SLOWER
TM SLOWER, TE FASTER

FIG. 31

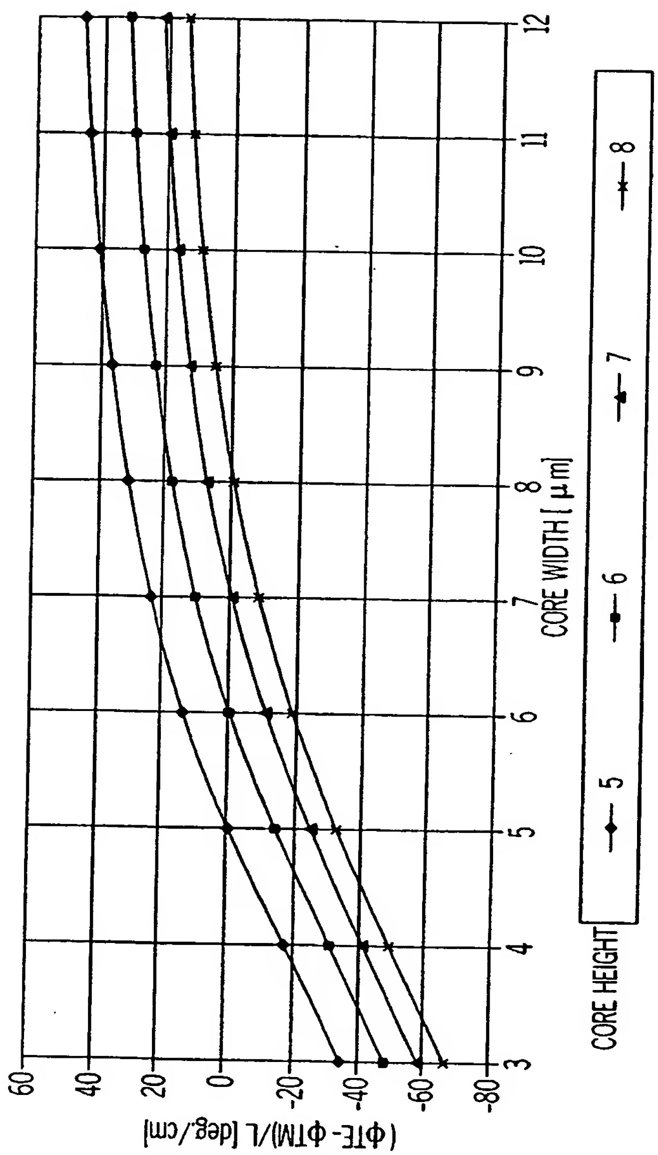
(φTE- φTM)/L [deg./cm]
60
40
20
0
-20
-40
-60
-80
3
4
5
6
7
8
9
10
11
12
CORE WIDTH [μm]
CORE HEIGHT
5
6
7
8

FIG. 32

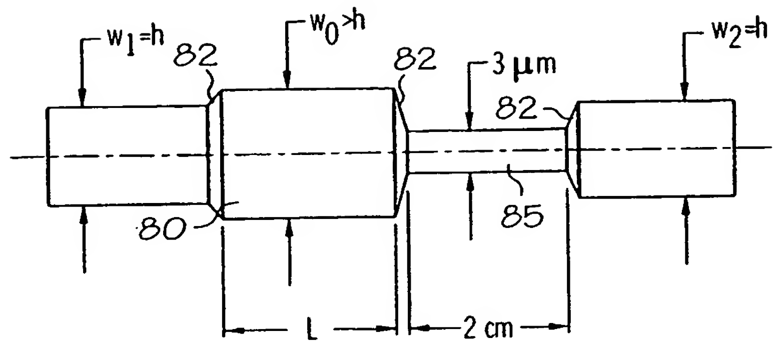


FIG. 33